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# GOALS AND MEANS IN THE CONQUEST OF SPACE

*by R. G. Perel'man*

*"Nauka" Press, Moscow,* 1967

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# GOALS AND MEANS IN THE CONQUEST OF SPACE

By R. G. Perel'man

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"Nauka" Press, Moscow, 1967

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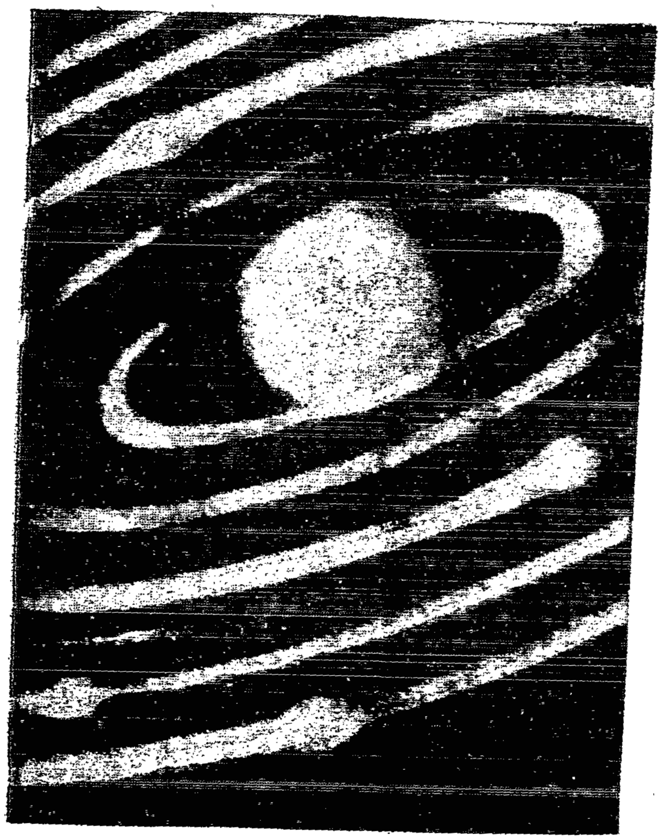
"What had seemed unfeasible for centuries, what yesterday was only a daring dream, today has become a real task, and tomorrow it will be carried out".

K. Sergeyev



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# 1.

## ASTRONAUTICS

(Developments and Goals)

### The Development of the Space Era

The reader is certainly familiar with the history of the development of man's ideas about the world. /5*

Following the development of natural sciences and means of transportation, and after geographic discoveries, ideas were developed about the structure of the space around us. This led to new discoveries. Science and technology developed at an ever-increasing speed, necessitating the corresponding change in social systems.

Figure 1 illustrates this characteristic aspect of technological progress. Different eras are plotted on a logarithmic scale along its horizontal axis, and examples of the boundaries to social systems are marked on this scale in connection with the evolution of mankind. Different eras in the development of ideas about the world and the dates of some principal technological discoveries are shown here. Along the vertical axis, on the same scale, we see the increase in distances covered by travelers and the first astronauts, the altitudes reached by satellite-probes and research rockets and, finally, the greatest payload capacities of rocket apparatus, as predicted for the near future.

It is difficult to select a comparison which characterizes the increase in tempo of technological progress clearly enough. Let us suppose that the entire cycle of the development of mankind, which is depicted on Figure 1 from primitive times to the present, extending over about 100 thousand years, were "squeezed" into 50 years of the life of one man. We could then consider that this man has been living under capitalism and then socialism only during the last month.

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* Numbers in the margin indicate pagination in the foreign text.

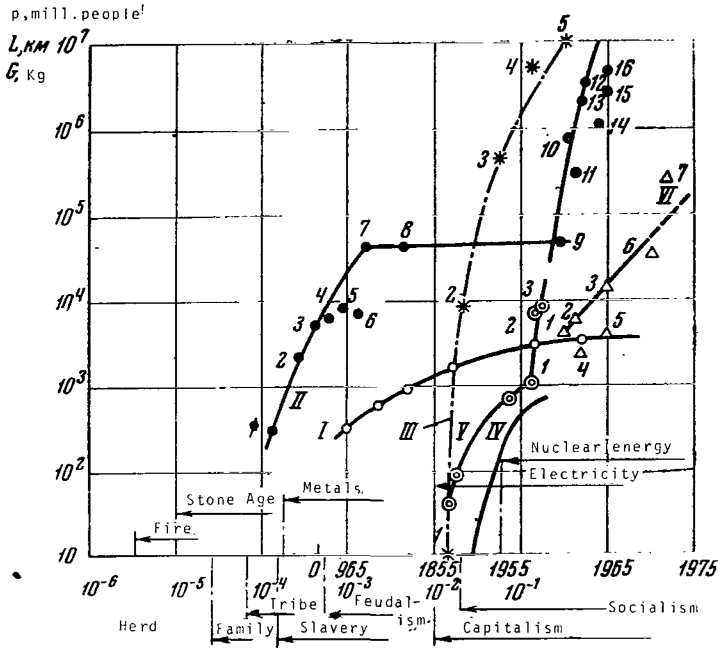


Fig. 1. Scientific-Technological Achievements of Mankind
(I) Population of the Earth. (II) Distances Travelled by Man (1 - example of "hunting"-radius of a tribe; 2 - Ancient Egypt; 3 - Ancient Greece; 4 - Ancient Rome; 5 - the travels of Marco Polo; 6 - the travels of Afanasiy Nikitin "over three seas"; 7 - Magellan's voyage around the world; 8 - the voyage of I. Kruzenshtern and Yu. Lisyanskiy around the world; 9 - spacecraft "Vostok-1", pilot Yu. Gagarin; 10 - "Vostok-2", pilot G. Titov; 11 - "Friendship-7", pilot J. Glenn; 12 - "Vostok-5", pilot V. Bykovskiy; 13 - "Vostok-6", pilot V. Nikolayeva-Tereshkova; 14 - "Voskhod-1", Commander V. Komarov, Doctor B. Yegorov, Scientist K. Feoktistov; 15 - "Gemini-4", pilots J. McDivitt and E. White; 16 - "Gemini-6", pilots G. Cooper and C. Conrad). (III) Increase in Range of Radio Communications (1 - Invention of the Radio by A.S. Popov; 2 - Establishment of Trans-Atlantic Radio Communications; 3 - Radar Detection of the Moon; 4 - Radar Detection of Venus; 5 - Reliable Connection with Automatic Interplanetary Stations). (IV) Altitudes Reached by Radiosondes. (V) Altitudes Reached by Single-Stage Rockets and the First Soviet Artificial Earth Satellites (1 - First Soviet Satellite; 2 - Second Satellite; 3 - Third Soviet Artificial Earth Satellite). (VI) Payload Capacity of Rockets (1 - Spacecraft "Vostok-1"; 2 - Soviet Space Base used for launch to Venus, 6.5 tons; 3 - Space Laboratory "Proton-1", 12.5 tons; 4 - Single-Passenger Craft "Mercury", 1.3 tons; 5 - Two-Passenger Craft "Gemini", 3.2 tons; 6 - Three-Passenger Lunar Craft "Apollo" Project, 38.5 tons; 7 - USA Project).

It can be said that the flame of progress, which smouldered and flared for centuries, has raged like a forest-fire during the last 50 years; during the last few decades, a real "explosion" has taken place in science and technology. This "explosion" can also be seen in the development of means of communications, engines and transportation. It has brought mankind irrevokably closer to the gateways to outer space. And then came the moment when the first astronauts went beyond the boundaries of the small biosphere - the envelopes of the Earth. /7

Even before the flights into outer space, scientists on the Earth began to reproduce cosmic conditions and processes. Superlow and superhigh temperatures, high vacuum - the rarefied state of a gas characteristic of interplanetary space - were studied in science and used in technology; interplanetary and interstellar plasma - the "fourth state of a substance" - was investigated intensively. This brought about new ways of designing new types of space engines. Scientists were trying to reproduce the thermonuclear processes which occur in the interior of stars on the Earth. This grew into the need for power engineering on the Earth.

In the course of time, geocosmology arose - a vast branch of science which studies the Earth is interation with outer space and uses knowledge about the Earth to investigate the latter. Geologists-tectonicists now examine orogenesis with a consideration of the movement of the Earth as a cosmic body. Earthquakes - seismic processes on the Earth - are evaluated with a consideration of the movements of the Moon and Sun.

It is doubtless that many terrestrial problems will be solved by studying the biogenospheres of other planets. For example, if a synchronism of temperature drops on Venus, Mars and the Earth is established, this will prove that glaciations on the Earth were caused by cosmic factors.

Reasons are being advanced for a connection between cosmic radiation and the arisal, as well as the evolution, of life on the Earth. In 1957, I.S. Shklovskiy and V.I. Krasovskiy proposed a hypothesis which explains the extinction of reptiles at the end of the Cretaceous period by a persistent increase in the level of cosmic rays by tens, and perhaps hundreds, of times. This /8
could occur if, at a distance, say, of 5-10 parsecs from the Sun, one of the stars flared up as a supernova.

The activity of mankind is in itself a cosmic factor. Intelligent beings have transformed our small Earth into a source of radio emission which is second in capacity only to the Sun in the solar system. The thousands of meter-range remote-control transmitters which operate on the Earth have mades its radio emission a million times greater than that of Mars and Venus. During the quiet Sun years, the radio emission of the Earth also surpasses the solar radio emission.

As the Earth revolves in front of the extraterrestrial observer, the intensity of its radio emission changes, since Asia and Africa have a smaller number of radio installations than Europe and America. These characteristics of the Earth indicate that it is populated by intelligent beings.

On the threshold of interplanetary flights, the sciences which try to predict the conditions under which astronauts will find themselves on different planets have acquired particular significance.

It is doubtless that the very next generation of scientists will be able to apply the most resultative expeditionary research method in order to solve complex space problems. And then the problem which has been involved for some thousands of years with the geography of the Earth will be raised in a new manner - the problem of describing the natural conditions of newly-discovered territories. Naturally, it cannot conceal the basic problem - finding the laws of evolution of the biogenospheres.

The inclusion in the spehre of human activity of the space around the Sun and other celestial bodies is a regular stage in the development of mankind.

## Why are We Conquering Outer Space?

The question is often raised: why are so many people and materials used on expensive space-research projects? There are still many questions of vital importance to be solved on the Earth!

However, the problems of the Earth cannot be solved apart from the surrounding space. The civilization of the Earth cannot exist without making some headway, and science, including astronautics, /9
cannot stop in its development.

The development of space research is only part of the studies connected with an increase in the "vitality" of mankind, with a development of civilization and, consequently, with an increase of the productive forces on the Earth. In turn, scientific and technological advances in astronautics become a stimulus for the development of many other branches of science and technology.

Turning to the goals of space research, we can divide the practical purposes into the closest, the more remote, and the most remote. We will discuss some of the practical problems in more detail, considering the purpose and possible functions of artificial satellites of our planet operating for the communication systems controlling meteorological, geological and many other extremely necessary observations.

On a larger scale, we must keep in mind that rockets, satellites, automatic interplanetary stations and spacecraft carry out flights in order to find new laws of nature and, consequently, in order to better organize life on our planet. "Our time is the age of space flights, of studying the distance Universe, finding out about processes occuring in it, and then applying this knowledge to modern technology", wrote the Academician V.A. Ambartsumyan.[1]

Scientists are finding more and more new natural processes in outer space which still have not been reproduced on the Earth. The interaction between charged particles and magnetic fields appears very clearly in outer space; this has yielded a great deal of data for a new outgrowth of physics - magnetic hydrodynamics. It is now used in metallurgy, welding and power engineering. The overdense substance contained in the interior of some stars, which is a million times more dense than any terrestrial substances, a gas whose density is a billion times less than that obtained under the best laboratory vacuum, solar vortices - a study of these and many other cosmic phenomena, particularly neutrino physics and its role in astrophysics, promises the most extraordinary discoveries. They will be widely used in industry, agriculture and medicine. /10

We can assume that certain compounds which are now scarce will be found on planets which have developed under conditions other than those for the Earth. Perhaps it will be necessary to undertake automatic methods of processing raw materials on such planets. Specialists will have at their disposal a high vacuum which still has not been realized under laboratory conditions on cosmic bodies without atmospheres. Possibly, they will be able to use physics in order to produce original accelerators.

These discussions on the "future purpose" of using outer space and cosmic bodies could continue ad infinitum. At the same time, we should mention that no single living person, not all of us together, can today predict in detail all that this sprout of terrestrial civilization will yield for the future. One thing is clear - it should grow into one of its greatest branches.

## Cosmography

Our Earth is one of the nine large planets in the family of the Sun (Table 1). It is an average distance of one-hundred and forty-nine million, nine-hundred and fifty thousand kilometers from the Sun. This distance is taken as the astronomical unity for measuring other cosmic distances. It is very small in com-

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[1] V.A. Ambartsumyan: Discovering the Laws of the Universe. Priroda, No. 12, 1963.

parison to the distance to the furthest of the large planets of the solar system - Pluto: the distance to it is about 5 billion km, i.e., 40 times greater.

The planets move roughly in one plane. For a graphic representation of the relative scales of the solar system, we will attempt to put all of it on one page of our book. For this, we must use a scale of $\frac{1}{4.10^{10}}$, i.e., one forty-billionth. The outer diameter of the solar system becomes equal to 15 cm, while the diameter of the Sun is only 1.7 microns, so that the Sun can be depicted by a dot made with a very sharp pencil. The planet closest to the Sun - Mercury - is at a distance of 0.7 mm from it, the morning star of Venus is further, at a distance of 1.25 mm, and the orbit of the Earth is almost 2 mm, while Mars is a radius /11 of 2.85 mm away. The huge planet of Jupiter, out of which almost 1400 such globes as the Earth can be "rolled", is at a distance of 9.4 mm and, finally, the furthest planet, or Pluto, revolves at the very edge of the page, 7.5 cm from the Sun. Spacecraft which overcome and use the attractive force of the Sun and the planets, the fields of gravitation, also move in interplanetary space.

Interplanetary space is vast, but it is scanty in comparison with interstellar distances. The ancient Arabic astronomers called the system of the closest (to us) multiple star of Centaurus, which consists of three self-luminous stars, the star of Ptolemaic. The beam of light from the smallest of these stars, the reddish star Proxima Centauri, is 4.27 years from the Earth, while the distance from it to the Earth is 270 thousand times greater than the distance from the Earth to the Sun, which is about 40 billion km. This means that the distance to Proxima is 4000 times greater than the entire diameter of the solar system.

The distances to stars are qualitatively different when compared to the interplanetary distances inside the solar system. Actually, if we put the solar system on one page, as we have done, then our Galaxy decreases in diameter roughly to 11,000 km in the corresponding reduction, i.e., can be placed roughly over the territory of the Soviet Union. The diameter of our planet is then about 1/10 of a micron, while Proxima Centauri is a distance greater than 650 m from the page we are reading.

The problem of a flight to stars is so complex that it is completely natural in the beginning to estimate, not so much the possibilities of a flight from one end of the Galaxy to another, but how to reach the system of the nearest star. Naturally, the possibility of the existence of a planetary world, life and civilization in the system of α-Centaurus should be evaluated more carefully, if possible, since this multiple system is the first proposed goal of investigatory galactic voyages.

TABLE 1. SOME INFORMATION ON THE LARGE PLANETS OF THE SOLAR SYSTEM

| Planet | Diameter, km | Mass in Units of the Mass of the Earth | Density, g/cm$^3$ | Average Distance from the Sun, million km | Distance from the Sun Compared to the Distance Earth-Sun | Time for Revolution Around the Sun, years | Period of Revolution Around Axis | Number of Satellites |
|---|---|---|---|---|---|---|---|---|
| Mercury.. | 4 800 | 0.05 | 5.5 | 57.87 | 0.39 | 0.24 | 88 days | 0 |
| Venus.... | 12 200 | 0.81 | 4.9 | 108.14 | 0.72 | 0.62 | 200-300 days | 0 |
| Earth.... | 12 753 | 1.00 | 5.5 | 149.599* | 1.00 | 1.00 | 23 hr 56 min | 1 |
| Mars..... | 6 800 | 0.11 | 3.9 | 227.80 | 1.52 | 1.88 | 24 hr 37 min | 2 |
| Jupiter.. | 142 700 | 318.4 | 1.3 | 777.80 | 5.20 | 11.86 | 9 hr 50 min | 12 |
| Saturn... | 120 800 | 95.2 | 0.7 | 1428.47 | 9.54 | 29.46 | 10 hr 14 min | 9 |
| Uranus... | 49 700 | 14.6 | 1.1 | 2873.19 | 19.19 | 84.02 | 10 hr 74 min | 5 |
| Neptune.. | 44 600 | 17.3 | 1.6 | 4501.51 | 30.07 | 164.79 | About 15 hr | 2 |
| Pluto.... | 5 870 | 0.9? | ? | 5908.14 | 39.70 | 249.7 | ? | 0 |

* One astronomical unit is equal to 149,599,300 km (measurements carried out in 1961 under the direction of Academician V.A. Kotel'nikov).



/12

The two most massive stars of this system are so far removed from each other than there can be planetary orbits lying in the "life zone" around each of them. However, the system of α-Centaurus is relatively young, and the stars composing it have not become stable; therefore, it is most probable that there are still no such planets on which life would be established in this system. Nevertheless, the closest, Centaurus, obviously should be the first target for an investigatory interplanetary flight. Perhaps in the distant future its planets will become the base for penetrating to other, further removed planetary systems, where there may be life and intelligent beings. /13

The thinkers of ancient times, Democritus and Epicurus in Greece and Lucretius Carus in Rome, developed the idea that an innumerable amount of worlds similar to the Earth could be formed. Modern science has confirmed the correctness of these judgements. All the stars which are visible to us, including the Sun, form a gigantic system - the Galaxy (Milky Way), which consists of more than 200 billion stars. The stars are thicker (denser) around the center and the plane of some equator of the Galaxy, forming a disc which is similar in shape to a lens.

Examining the Galaxy from above, we would see something in the nature of a spiral. A beam of light moving at a speed of about 300,000 km/sec (or, more precisely, 299,793 km/sec) and passing $0.36 \cdot 10^{12}$ km per year, cuts across the Galaxy, almost in 90 thousand years or, as astronomers say, this distance is 90 thousand light years. The thickness of the galactic disc is estimated as roughly 10 thousand light years; therefore, the space occupied by the Galaxy is about $30 \cdot 10^{12}$ $m^3$, i.e., 30 trillion cubic light years. The mass of the Galaxy is about 260 billion masses of the Sun.[2] The diameter of our neighbor in space - the Andromeda nebula - is roughly 1.5 times greater. Nevertheless, such large galaxies as ours are found roughly once in a hundred times, or even more rarely.

In order to measure the distance between stars, the radius of the Earth's orbit, which is roughly equal to 150 million km, /14
is used as the basis. The distance from which this radius is seen at an angle of 1 sec is called the parsec and is used in stellar astronomy. One parsec is equal to $3 \cdot 10^{13}$ km, i.e., 30,000 billion km. Light passes this distance in 3.26 years.

The Sun and most of the stars close to it revolve around the center of gravity of the Galaxy at a speed higher than 200 km/sec and made a complete revolution in roughly 300 million Earth years.

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[2] See Pskovskiy, Yu.P.: What are the Dimensions of our Galaxy. Priroda, No. 11, 1964.

This period is called the cosmic year. The age of our planet, obviously, is on the order of 20 cosmic years.

It was found in the 1920's that, in addition to our Galaxy, there are just as huge formations of a spiral and oval shape, consisting of tens of billions of stars, in the space beyond the boundaries of the Milky Way. Our Galaxy was found to be a common island of stars in an infinite groud of islands of the ocean of the Universe. Three of them - the Andromeda nebula, and the Major and Minor Magellanic Clouds, which are seen with the naked eye as hardly-noticeable nebuluous spots - are similar in their structure to our stellar system. The distance to the Magellanic Clouds is roughly 2.5 times greater than the diameter of our Galaxy. In the model where our solar system is so reduced that the Earth seems to be on the first orbit of the Bohr atom, the distance to the Andromeda nebula is a little more than 6 m.

It has been established that most of the galaxies move away from us, while the speed of their dispersion increases with an increase in the distances, roughly by 100 km/sec with each million parsecs. The record speed of withdrawal was achieved by one of the galaxies which is 5 billion light years from us, about 150,000 km/sec - almost half the speed of light. In all, there are about ten billion galaxies in the sky within the field of observation. Radio telescopes have detected galaxies whose light comes to us in about 3-5 billion years. This means that we observe them as they were long before the arisal of man on the Earth.

In 1953, the French astronomer Voculaire proved the existence of a complex system of galaxies - the Metagalaxy - with dimensions /15 on the order of ten billion light years, in which our Galaxy is included. The boundaries of the Metagalaxy are still within the potential range of astronomical instruments.

The solar system is at the edge of our Galaxy, at a distance of about 30,000 light years from its center.

The stellar density in the Galaxy is very irregular; it reaches 2 thousand stars per cubic parsec in the region of the central nucleus. This is about 20,000 times more than that in the neighborhood of the Sun, where the average distance between stars is close to 6 light years. It is some tens of millions of times greater than the average sizes of the stars.

"Taking the solar system as the average space per star in the Milky Way, we can say that the Earth is lost in it like a drop of water in the oceans"[3], wrote K.E. Tsiolkovskiy. Some of the

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[3] Tsiolkovskiy, K.E.: Grezy o zemle i nebe (Day-Dreams about the Earth and Sky). Moscow, Akad. Nauk S.S.S.R., 1959.

stars form separate groups, accumulations. Among the stars which indisputably belong to our Milky Way, there are those which move so rapidly that they cannot revolve around the center of the Galaxy. They are probably new-comers from the cosmos which move through the space of our and other galaxies, encountering them in flight.

The stars, just as our Sun, represent incandescent gaseous spheres consisting of the same elements as the Earth. They do not differ particularly in mass. There are stars which are smaller in mass than the Sun by a factor of 5-10, and others which are some tens of times greater than it. Thus, the Sun is the most common star in terms of mass.

Now let us turn to a problem which is exceptionally important for astronautics - estimating the number of planet worlds in the Galaxy; possibly, some of them will become the targets for long-range space flights in the future.

The relatively low speed of revolution distinguishing these stars indicates that many of the stars certainly contain planets. Possibly, as in the solar system, a substantial amount of the moment of momentum of the system "fell to the lot" of the planets surrounding them. We should mention that the moment of momentum can be imparted to the star not only by planets but also by the /16
interstellar gas due to the interaction of the magnetic fields of the star with it.

The studies of the Swedish astronomer Holmberg, for example, are a convincing proof of the existence of unseen satellites of stars. In 1938, while studying photographs of the movements of the stars closest to us, he found that many of them displayed wave-like movements apparently due to the attractive force of invisible luminous satellites revolving around these stars. He calculated that the invisible satellite of our nearest neighbor - Proxima Centauri - is 12 thousand times less bright than the Sun, and has a mass comparable to that of Jupiter (roughly twice greater).

The Soviet astronomer A.N. Deych showed that one of the closest stars to us, 61 Cygni[4], has planets whose total mass is roughly 50 times less than the solar one. If we assume that this star has one satellite, then it should move at a distance of about 450 million km from it, completing one revolution around the star in 25 years, which is close to the rotation period of Saturn.

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[4] The designations of stars are taken according to the star catalogue of the French astronomer Lalande (1732-1807), who determined the position of more than 47 thousand stars.

TABLE 2. THE CLOSEST STARS TO THE EARTH AND THEIR INVISIBLE SATELLITES

| Distance from the Earth in Light Years | Star | Mass of Satellites Compared to Total Mass of the Satellites of the Sun | Mass of Satellites in Units of the Earth's Mass | Star-Satellite Distance Compared to Sun-Earth Distance | Star-Satellite Distance Compared to Sun-Jupiter Distance | Period of Revolution in Years | Author of Calculations |
|---|---|---|---|---|---|---|---|
| 0 | Sun | 1 | 445 | 5.2 | 1 | By Jupiter 12 | Holmberg |
| 4.27 | Proxima Centauri | 1.44 | 640 | - | - | - | - |
| 6.0 | Star of Bernard | 1.06 | 478 | 4.4 (major semiaxis) | 0.85 | 24 | Van de Kamp |
| 7.7 | Wolf 359 | - | - | 0.3 | 0.06 | - | Stearns & Olden |
| 8.2 | Lalande 21185 | 3.93 | 1750 | 0.13 | 0.025 | Little more than 1 year | Van de Kamp |
| 11.1 | Double Star 61 in Cygnus Constellation | 1.5 | 670 | 3 | 0.58 | 25 | Holmberg, Strend Studied by A.N. Deych |
| 15.65 | +20°2465 | 2.47 | 1100 | 0.52 | 0.1 | 26.5 | Rayle |
| 16.4 | Double Star 70 in Ophiuchus Constellation | ~7 | ~3100 | - | - | 17 | Rayle & Holmberg |

In order to observe the wave-like movements of stars at astronomical distances, a staggering amount of effort on the part of specialists is necessary. A careful study of 240 of the closest stars showed that about 60 of them apparently have such periodic oscillations. The German astronomer Schlesinger computed the movements of about 6 thousand of the closest stars, as if measuring the thickness of a hair from a distance of 2.5 km.

In 1964, the American scientist Van de Kamp established the presence of an invisible satellite with a mass which exceeds that of the Earth only by a factor of 500 in one of the closest stars - the star of Bernard - a red dwarf. The mass of this star is 0.15 of the solar mass, and the radius is 1/6 that of the Sun. It is particularly important that the mass of the satellite discovered by Van de Kamp is close to the mass of Jupiter and such that intensive thermonuclear stellar reactions cannot occur in its interior. Apparently, this was the first giant cold planet belonging to a neighboring star which was detected from the Earth.

Table 2 shows the stars closest to the Earth and gives some data on their invisible satellites, including the satellite of the star of Bernard. /18

We should mention that, in each case when an invisible satellite is noted by the oscillations in the position of a star, this still does not mean that the star has one satellite. It is possible that it is actually the center of the entire planetary system. Thus, if there are two planets the size of Jupiter and Saturn in the system of 61 Cygni, then their combined action would yield the same effect as the action of one larger planet. The division of the proposed mass of the satellites into several objects increases the chances that the mass of each of them does not reach the stellar mass and, consequently, it remains a planet.

Van de Kamp's discovery of a planet of one of the closest stars is a ponderable indication that there should be numerous planetary worlds in the Galaxy. In turn, this indicates the possibilities of the arisal of extraterrestrial life and extraterrestrial civilizations.

## The Great Reserve of Life

Outer space should be a great reserve of life. F. Engels

As if we did not want to consider some planet to be populated by livings beings, particularly that planet on which the conditions for this are obviously advantageous, we should draw our conclusions only on the basis of a critical evaluation of facts, which observations give us.

The question of life on Mars should be finally answered, naturally, before astronauts land on it. We will be able to judge

indirect appearances of Martian life according to photographs of Mars and its satellites taken "point-blank" from on board an automatic interplanetary station (AIS). The experimental detection of lower forms of life will possibly be carried out with the aid of bio-elements; these are containers with culture medium which are controlled by radio methods. Dumped on the surface of Mars, they /19
take in a "portion" of Martian bacteria within a certain time, and can give a signal on their reproduction. Other methods of detecting life have also been suggested.[5]

Nevertheless, the ultimate and comprehensive answer about the existence, forms and peculiarities of Martian and Venusian life will be found by researchers who will be able to work "on location" in the not-too-distant future. This will put an end to the prolonged discussions.

The interplanetary era has arrived. The time is not too far away when scientists will penetrate into the most complex questions of the universe, not only observing other planets from the Earth, but also travelling to them. Therefore, the question of the existence of, not only life, but also intelligent matter in the Universe is now advanced as one of the reasons for the expediency of interstellar flights.

We have already spoken of the multiplicity of planets. However, if the multiplicity of the stars of our and other galaxies is accompanied by planets, then, obviously, there is not only life but also thinking beings somewhere in the Universe beyond the boundaries of the Earth.

"Is it probable that Europe is inhabited while other parts of the world are not? Can there be one island with inhabitants and many others without them? Is it probable that one apple tree in the infinite garden of the universe is covered with apples, while an infinite number of other trees are only green? Spectral analysis shows that the substances of the Universe are the same as the substances of the Earth...Life is teeming everywhere in the Universe. Life is infinitely diversified", predicted K.E. Tsiolkovskiy.

Life can arise everywhere where the conditions necessary for it exist. What about the conditions? Based on terrestrial experience, we know that life, in particular, can arise on that heavenly body where the chemical elements which make up protein-bodies exist, on the condition that the same elements have not formed chemical compounds which kill proteins.

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[5] Atomes, Vol. 206, No. 19, pp. 15-20, 1964.

The basis of living organic matter on the Earth is proteins and nucleic acids. Their "skeleton" is made up of carbon atoms, which have the capacity to compound into long and branching chains, by which innumerable amounts of compounds can combine. The source of energy which sustains life on Earth is solar radiation. It is /20
used by a whole class of living matter - plants.

Green leaves, catching the rays of the Sun, synthesize organic compounds from the solutions of salts yielded by the roots and the carbon dioxide of the atmosphere. In this case, the carbon is included in the composition of the protein molecules, while the oxygen is yielded freely, producing the oxygen portion of the atmosphere of the planet. This produces the prerequisites for another energy chain. A second class of living beings - animals - use it. Leading a "parasitic" type of life, they oxidize the prepared organic compounds of plants and other animals due to the (also prepared) oxygenous atmosphere. The source of energy for them is slow oxidation, combustion of organic compounds in an organism.

Consequently, for the arisal of life, it is necessary that there be the corresponding atmosphere which is amenable to decomposition by the effect of an external energy source (Sun), and also a moderate temperature range, so that water, the base of the internal medium in which metabolism occurs, is in liquid state. Since, in all probability, life originates in water, increased gravity (size of the planet) cannot prevent its arisal. Obviously, active life can arise and develop on a planet if the temperature on its surface and the magnitude of solar irradiation do not deviate greatly from an average value (for example, roughly in a range from -30 to +70° C). This planet should have an orbit in which a roughly identical distance is maintained between the planet and the star heating it.

It can be assumed that a vast majority of the planets, as the planets of the solar system, move around their suns on orbits close to circular ones, in one direction and almost in one plane. Then, around the central star of the system, there will be an annular "corridor" with acceptable illuminance, temperature, etc., within which some of the planets are found and where a life zone is possible. The star of such a system should be "old", stable, what the Sun began as billions of years ago. A vast amount of stars fulfill this condition.

However, up to 80% of all the stars of the Galaxy represent /21
two or more stars, revolving around a common center of gravity, which are relatively close to one another. Stable planets of such stars should move along complex trajectories, first approaching their suns and then moving away from them. In this case, the temperature on their surface should change substantially, which means that the conditions for the arisal and development of life on them are very disadvantageous.

Up until recently, it was considered that habitable planets could not exist around multiple systems. However, the American astronomer Su Shuhuan showed that, in those cases when the orbits along which multiple stars move relative to one another are close to circular, their planets can move, in turn, along such orbits that their temperature changes within limits which allow the arisal of active life.

This condition can also be observed if two stars composing a binary system are sufficiently distant from one another, i.e., make up a "large pair". Although only a minority of multiple systems apparently have planets suitable for life, the discovery of Su Shuhuan allows us to increase the suggested number of such planets to a great extent.

Thus, life on Earth was developed according to the oxygen-water variation, because oxygen and water first and foremost advance authoritatively here; oxygen as the chemically active part of the carbon dioxide of the primordial atmosphere, which is easily split up by photosynthesis, and water as the predominant solvent. It is not denied that protein life could arise on the basis of other nucleic acids, not those on the Earth, and there can be other substances subjected to photosynthesis of another form of regeneration by the effect of external energy sources. Naturally, if the conditions on another planet differ greatly from terrestrial ones, life should also differ greatly in its forms and appearances from those which reign on our planet. It is doubtless that the protein life of the Earth is only one of the possible variations of life.

Breaking with the geocentric position in chemical and biological concepts, we can attempt to reconstruct the chemical appearance of other worlds, characterized by other statistics for the abundance of chemical elements. In such a world, the crust /22 of the planet would be made of other minerals, its depressions would be filled with other liquids. The atmosphere would be formed of other gases. The biology and biochemistry of the planet would be determined by the chemical composition of the planet, the nature of the radiation of its sun.

Naturally, under such conditions differing completely from those on the Earth, a jump from non-living to living could also occur in non-protein forms.

Recently, certain specialists, particularly Doctor of Chemical Sciences Ye.D. Kaverzneva, have turned repeatedly to a discussion of a hypothetical proposition on the development of life which is also based on silicon compounds. Stable molecules can be constructed from potassium in the form of long chains which are resistant to high temperatures. Silicon partially satisfies the requirements necessary for the formation of high-molecular compounds and, perhaps, is also capable of becoming the "skeleton" of living matter. Let us remember that the silicon content in the atmospheres of stars and nebulae is only 5-6 times less than the carbon content. Silicon life is one more form of the infinitely varied life which apparently can develop in the Universe.

The Academicians A.I. Oparin and V.G. Fesenkov showed that the probability of a simultaneous combination of all the conditions (mutually independent) under which living matter can arise even in its most diversified forms in the systems of stars included in the Galaxy is about one hundred-thousandth or one millionth. Using this assumption, we nevertheless find according to very conservative estimates that there should be more than one-hundred thousand inhabited planets in our Galaxy on which living organisms have arisen. If we consider the reciprocal dependence of factors necessary for the arisal of life, then the number of such planets increases at least by a factor of one thousand.[6]

H. Shapley formed an interesting hypothesis concerning the possibility of existence of dwarf stars[7] whose temperature is not too high for complex molecules capable of becoming the basis of life. In his opinion, it can be assumed that, with a decrease in the brightness and size of heavenly bodies, their number should increase. Some "dull" stars we know of - red dwarfs, which have brightnesses one-millionth the brightness of the Sun - are studied only on very powerful telescopes and are usally not considered in star catalogs. With a decrease in brightness and size to dimensions close to those of planets, the dwarf stars do not emit visible light, do not have a notable gravitation effect on the movement of other stars of the Galaxy and therefore have still not been detected. If such a star has dimensions roughly 50 times greater than Jupiter, its internal heat could provide temperatures which are admissible for the development of life on the surface of the star. "Such bodies", Shapley noted, "doubtless exist, and not only in the planetary systems of stars, but also as single bodies not connected with them. Such bodies can be detected with the aid of radio telescopes, and perhaps radio-astronomers have already observed them as the sources of radio emission, but did not identify them as what they actually are". Life can arise not only on the surface, but also in the atmosphere of such dwarf stars (or giant planets). /23

[6] See Tsitsin, F.A.: The Cosmos and Intelligent Beings. Priroda, No. 11, 1965.

[7] Shapley, H.: Life on Dwarf Stars. In the Book: Nauka i chelovechestvo (Science and Humanity). "Znaniye", 1964.

Shapley suggested that there should be "an innumerable amount" of such independent self-heating planets. Life on them would be very unique, since the source supplying its energy would be inside the heavenly body and the energy on its surface would appear in radio-frequency range. This world would seem as strange to us as we would to it. However, this again only emphasizes how the products of cosmic evolution can vary infinitely.

Naturally, we can draw a final quantitative conclusion on the abundance of life in the Galaxy only when we know the rules for the origination of life. Professor A.S. Kompaneyets considers that, in connection with the advances in biology, the problem of /24
the probability of the arisal of life will be solved in the very near future - in 10 years or perhaps less. In order to estimate the probability of such an event as the appearance of hereditary information, which is characteristic of any living matter, we must find the ways in which life originates in full. The discovery of life on one of the planets of the solar system would be an experimental confirmation of the idea that life in the Universe is abundant. The absence of forms of life in the near cosmos would move the answer to the question back to voyages to other stellar worlds.

We would like to mention that life which has arisen and been asserted has great "stability". "In the course of generations in geological time, organisms become adapted to the most unlikely conditions", said Academician V.I. Vernadskiy. According to his computations, the amount of living matter in the Earth's crust is $10^{14}$ - $15^{15}$ tons. Actually, the oxygen of our atmosphere is the product of photosynthesis of planets, while the outer layers of the Earth's crust are 99% processed by them. The leaves of a plant are shed during the winter, animals go into hibernation during the unpleasant time of the year, and man heats his home and makes pressure suits for astronauts. Once arisen, life becomes adapted and propagates, first over the entire planet, and then beyond its boundaries. Deserts are irrigated, man becomes strengthened and lives under the most disadvantageous conditions of the Antarctic cold or cosmic vacuum.

It seems to us that it is not obligatory to doom life which has arisen on a star to destruction, even in the case of the star itself dying off. It can proceed through interstellar space to other suns, on preset, advantageous orbits of satellites or advantageously-constructed planets, to multiply the advances of intelligence.

A basically new stage in the interrelationships between an organism and the medium begins with the arisal of intelligent beings, which affect the surrounding world most actively, intelligently changing the environment, making it suitable for habitation.

The production of energy on the Earth is doubled every 20 years, and the tempo of its generation is still increasing. It can be assumed that, in 200 years, possibly before, $3 \cdot 10^{12}$ KW will be generated and used on the Earth. This corresponds to 1% of the capacity of solar radiation incident on our planet. Based on the ever-increasing capacities of energetics, it is probable that the /25 future will find possible that which today is completely unfeasible, although does not contradict the laws of nature. We are speaking of the reconstruction of our, and then other, planetary systems, with the shift of the planets on those orbits which are most favorable for their population.

Thus, there is no end to life, no end to intelligence and the development of humanity. Its progress is eternal. Well, if this is so, then it is time to give some thought to a very remote but, in our opinion, basic goal of astronautics.

## Basic Goal of Astronautics

In 1964, the first all-union conference discussing the possibilities of establishing contact with civilizations of other planetary worlds took place at the Byurokan Observatory of the Academy of Sciences of the Armenian S.S.R. Eminent scientists, radio-astronometers, radio-physicists and astrophysicists took part in the work of the conference.

Why did there have to be such a meeting of scientists? Why has it become urgent and why are people now attempting to analyze the problems of contacts - communication with extraterrestrial civilizations - and the problems of flights to them? What will their solution give, even in general? Will there be efforts wasted by men on the way to this goal, will the final results be justifiable?

Such questions are now being raised, not only by people seized with an acute interest in future astronautics, but also by skeptics who consider the examination of these questions to be untimely.

Let us attempt to answer in brief the questions raised, and to discuss what is the basic goal of astronautics.

Doubtlessly, as science and culture grows, the need for combined studies of scientists both in each country and on the scales of the entire Earth will arise. The thought of carrying out an interplanetary voyage probably originated with the dream of exchanging achievements with thinking beings of other populated worlds, sharing our experiences with them, and drawing out their experience - the experience of intelligence accumulated on planet - islands of life and thoughts on the Universe. This is perhaps one of the /26 most stirring tasks and problems of our time.

The achievements of science, which now permit us to examine this problem on a scientific basis, and the vast interest in it have become the reason for the recent arisal of about one hundred studies written by well-known scientists on this theme.

Specialists have proven the existence of cold satellites of many of the stars closest to the Earth. Since life is a regular stage in the development of matter, the highest form of the development of living matter - intelligent beings - should arise on some of the planets distributed at different distances around the stars. Therefore, we can say that there is life in its highest forms outside the Earth, on other planets - satellites of stars, which means that we are not alone in the Universe.

It is probable that our civilization is one of the youngest in the Galaxy. Life arose on the Earth some billions of years ago, and humanity has lived only about 600 thousand years; before that, there were billions of years of development. K.E. Tsiolkovskiy, showing the great difference in the level of civilizations in different worlds wrote:"...All the developmental phases of living beings can be seen on different planets. What humanity was several thousands of years ago and what it will be after several million years, all this can be investigated in the planetary world..." Actually, in the Universe, where the development and arisal of stars and planets occurs non-uniformly and non-simultaneously, even on astronomical scales, the irregularity in the development of life should be even greater.

According to the probability theory, the average gap in periods of the development of civilizations should be about one-half the average period that each stage lasts. If this period is on the order of a billion years, then the most probable "average gap" is hundreds of millions of years. Thus, it can be anticipated that the intelligent civilizations of the majority of planets are incomparably more experienced than we are.

Penetration into outer space will expand our knowledge on the Earth, will yield an abundance of energy to terrestrial civilization, and new prospects for a better life design on Earth. Moreover, if people were able to visit one of the distant worlds, acquaint themselves with its achievements and bring back the fruits of its development to the Earth, then, once man had mastered them, he would make a huge jump forward, economizing the labors and /27 efforts of generations. Besides those advances in the knowledge of nature which will be made during the course of constructing the galactic crafts, will such a success really pay generously for the expenditures of the human mind and earthly material resources?

However, we must keep in mind that, no matter how vast the amount and content of interplanetary information, only the personal efforts of man will guarantee its mastery and technological progress in general.

Thus, the basic goal of astronautics is to make contacts with intelligent beings on other planetary worlds in the distant future.

The division of possible contacts of stellar civilizations into indirect and direct is far from complete and precise.

Obviously, only the term "indirect contacts" can be defined clearly. It is more correct, suitable and simple not to "classify" possible contacts but to enumerate them directly and describe the possible methods of establishing contacts, as well as maintaining and expanding communication with foreign-planet civilizations. Let us do so, arranging such methods in order of the complexity of realizing them and the amount of information which can be obtained with each one. Naturally, we are not considering in this case that the method called the first is simple and does not require particular efforts or a high development of civilization for its realization.

Thus, the first of the possible methods is communication with the aid of electromagnetic vibrations - radio-frequency waves or collimated light rays directed from one stellar civilization to another. This method presupposes that three types of signals can be used:

"passive" signals from planets in the form of radio emission due to the existence of technologically developed civilizations. These signals, in particular, can be the result of the operation of television apparatus;

signals containing information transmitted by all or some civilizations, which can be overheard;

special signals, or "calls", transmitted in order to establish contacts, and signals, which are exchanged after contacts are established on the communication channels with the aid of radios or optical collimated rays (lasers). /28

Figure 2 shows graphs which were proposed by the Australian radio-astronomer Braisewell. They allow us to determine the distance $\underline{L}$ between a conditionally-assumed number of civilizations $\underline{N_c}$ in the Galaxy in light years and parsecs.[8] The more civilizations

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[8] Since there are still no scientific facts to determine the number of civilizations in the Galaxy, these assumptions are given only in order to evaluate the possibility and difficulty of establishing contacts for a varied, conditional number of civilizations.

in the Galaxy, the smaller the distance between them. The graphs show us the distance from such civilizations to the Sun. At the same time, we can determine the total number of stars $N_s$ which are at this distance from the Sun. The latter is particularly important for finding how complicated it will be to look for developed civilizations. We should mention that the number of civilizations $N_c$ should be in direct dependence on the average length of the technological era of their existence.

Let us assume, as an example, that the number of civilizations in the Galaxy is $10^{10}$-ten billion.[9] Correspondingly, we will take the average duration of the life of each as $10^{10}$ years. Then, the distance to the nearest civilizations from the Sun on the graph of Figure 2 is about 10 light years and, since there are several stars in this region of space, a search for a "neighboring" civilization is uncomplicated. Drake counted on such an advantageous case when he carried out the "OZMA" project in 1960 and attempted for several months to receive "intelligent" radio-signals with a 27-meter radio-telescope at a wave of 21 cm (frequency of 1420 megahertz) from two stars relatively close to us - $\varepsilon$-Eridani and $\tau$-Ceti.

If we assume that the duration of the technological era is only equal to $10^4$ years, then the number of civilizations decreases in proportion, and the distance to the closest civilization is about one thousand light years. Inside the sphere described by this radius, there are about 50 million stars, on each of which we must look for the necessary civilization. Naturally, it is an expensive, complicated and long procedure to carry out simultaneous observations of such a number of "suspected" worlds at a vast distance with the aid of directed beams. At the same time, it is difficult for the inhabitants of one of these remote worlds to give preference to our system from among the tens of thousands of suns. Perhaps it takes too long to look for one another without success.

Therefore, Braisewell recommended the method of automatic probes for establishing contacts with the civilizations.

A highly-organized civilization can send automatic probes, automatic interstellar stations to several thousands of the closest stellar worlds. The velocity of the probes should reach 200,000 km/sec. After a few decades, there could be a sufficient number of probes directed over all the "suspected" stellar worlds, e.g., in a sphere with radius of 100 light years.

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[9] This assumption is corroborated in the article by K.S. Bils entitled "Will there be an End to the World". See: J. Roy. Astron. Soc. Canada, Vol. 47, No. 2, 1953.

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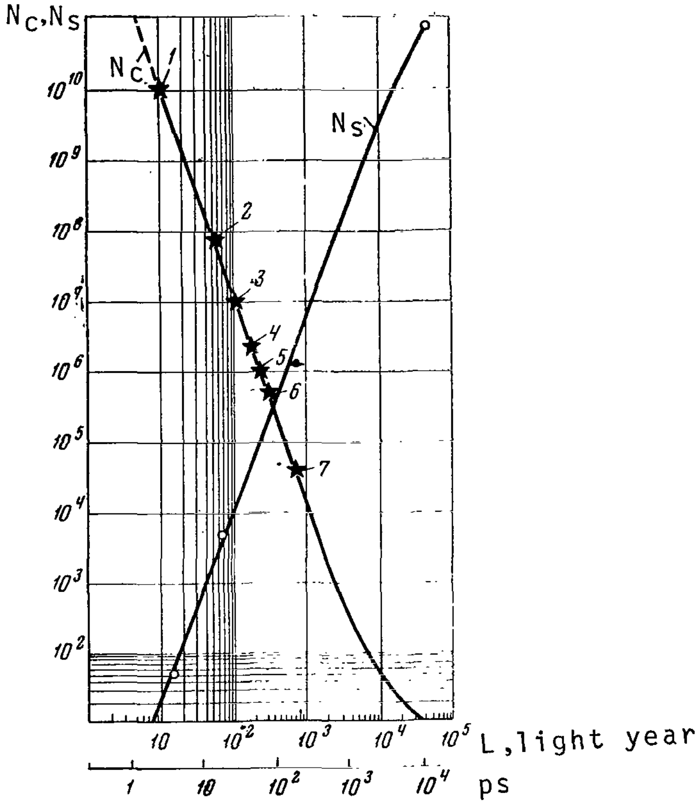


Fig. 2. Dependence of the Number of Civilizations in the Galaxy $N_c$ on the Distance Between the Nearest Civilizations According to the Data of Different Scientists ($N_s$ is the Total Number of Stars over this Distance.
(1) K. Bils ($N_c = 10^{10}$); (2) A. Shapley ($N_c = 7.5 \cdot 10^7$); (3) K. Sagan ($N_c = 10^7$); (4) A. Cameron ($N_c = 2 \cdot 10^6$); (5) A. Oparin and V. Fesenkov ($N_c = 10^6$); (6) I. Shklovskiy ($N_c = 5 \cdot 10^5$); (7) Horner ($N_c = 4 \cdot 10^{10}$).

The probes, guaranteed reliable protection from injuries caused by meteorites and equipped with radio sets of great resource, should carry out radio reconnaissance in order to detect signals from the planets of stellar systems whose satellites they have become. The apparatus of the probe should reproduce the signals and return them back to the planet. The apparatus can also transmit additional information. In particular, the probe could transmit the image of the stellar sky sent to it in the control with a special indication of the star from whose planet it was sent. The probe can take the energy necessary for operation from the star whose satellite it became. /30

This method of communication cannot be considered indirect. It presupposes the existence of small but nevertheless "real" apparatus capable of surmounting the interstellar spaces.

As has been confirmed by the methods now used in studying the planets of our system, the echo method can also be used successfully after establishing contact and direct radio communication between different planetary civilizations for the exchange of "concentrated" information and material objects. Thus, the echo method can also precede the establishment of radio communications, simplifying the search and expanding these connections.

Finally, let us discuss the method of direct searches for intelligent civilizations with manned craft.

The planning and accomplishment of this method are important, not only because it remains the best means of acquiring information and studying other worlds before producing compact and intelligent information devices which surpass the capacities of a man equipped with instruments in terms of potentials and weight characteristics. The planning of this method is also important because it provides greater adjustability and "stability" than man. /31

Moreover, only such a method can permit us to carry out extensive studies of the planets on which there is no technologically developed civilization. The fact is that the possibilities of a long-range investigation of objects, particularly those which are vast distances away, are very limited. This is proven even by the fact that, despite the comparatively short distance to Mars, astronomers still cannot finally establish whether or not the origination of its satellites was natural, although it can be shown that Phobos appeared on its orbit roughly 100 million years ago - much later than the planets of the family of the Sun were developed.

The advantage of the method of a flight to the stars with a return also involves the case when there is a civilization but it is insufficiently or uniquely developed, so that it cannot answer an inquiry. An acquaintance with "answer-less" civilizations could be a source of valuable information, and the significance of the only possible method of contact in this case is very great.

Man is always seeking to set up a cybernetic system between himself and the most complex and dangerous phenomena of nature. However, all the inexhaustible potentials of man are also needed for consolidation in the infinitely complex space. People need more than facts collected and systematized by automatic devices, documentary photographs and motion-picture films. People need living descriptions of new worlds, they need to feel the romance of the hitherto-unknown, the enticing breeze of wander-lust. And that is one more reason for using a study method which involves bringing man to other worlds. We should add that, in using this method, there can be an incomparably greater exchange of objects of material cultures between the civilizations.

We should turn to the assumptions made by Braisewell and von Horner on the vast possibilities of "feedback". The feedback effect means that important data can be obtained by exchanging /32 information with civilizations so that there is a sharp increase in the vital capacity of each.

I.S. Shklovskiy considers that, with the exceptional prospects of developments in automation, cybernetics and molecular biology, an evaluation of the possible time for existence of a civilization should be revised in favor of an increase. He also sees the possibilities of qualitative change in the forms of life in the Universe, and considers that intelligent life may appear not only in the same way as terrestrial life, but, ultimately, exceptionally stable artificial living intelligent beings could be produced. The scale of time for their technological development could be close to cosmic.

It is possible that some of the civilizations will be able to develop continuously, surviving the destruction of their stars. This would mean actual eternity of such civilizations. Moreover, even in the case of the destruction of our Galaxy, there could be migration of some part of the galactic civilizations by way of a trans-galactic flight. In other words, if a civilization is redistributed into a galactic one, then the periods of its existence could become comparable to the periods of the existence of the Galaxy.

The development of interstellar communication, astro-navigation and astronautics, which guarantee an investigation of planetary worlds of other stars and a vast exchange of information between civilizations of the Galaxy, will be able to provide such redistributions. A civilization founded on a nova could be based on the same technique. In this case, the questions of the need for migration, the selection and adaptation of the new stellar system for habitation, could be answered by several civilizations.

We should look for the possibility of lengthening the lifetime of civilizations and continuously surpassing their achievements not only in the extraordinary advances of science and technology, and not in the general "tendency toward order and good", on which the famous American astronomer Harlow Shapley is resting his hopes[10].

We can expect that the cosmic level of science and technology corresponding to the communistic future of civilizations will be able to perform operations which preserve such civilizations and their culture.[11] Moreover, by transforming the surrounding stars at first, producing artificial biospheres around them and increasing their energy reserve, civilizations will be able to propagate, encompassing the entire Galaxy with their activity. This could become a decisive triumph of the mind over non-living nature and even the rule for the development of intelligent civilizations of the Universe. /33

## The Space Program of Mankind (Technological Potentials)

By what means did man assert himself in the Universe? What permitted him to cross the Earth's threshold and set off to conquer outer space?

We will attempt to discuss the methods of carrying out the space program of mankind in a compressed form. Figure 3 will help us here. The limited range of steady flight is depicted in its lower part for different altitudes and speeds. How is its position determined? We will clarify the answer with the following example. During a flight at an altitude of 11 km at a speed of 8 M[12], the skin temperature of the aircraft would rapidly reach roughly 1000°C. Let us assume that great heating is inadmissible.

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[10] See Shapley, H.: Zvezdy i lyudi (Stars and People). Foreign Literature Publishing House, 1962.

[11] Braisewell and von Horner maintain the reactionary idea that it is sufficient, biologically speaking, to acquire intelligence for chances of survival to decrease sharply. In other words, they hold that every civilization ends with suicide. This idea is completely unfounded. On the contrary, it is doubtless that intelligence is a positive factor in development.

[12] The M number means the ratio between the flight speed and the speed of sound at a given altitude. In this case, the flight speed is 9 times greater than the speed of sound. For the Earth, the speed of sound is equal to 330 m/sec.

A further increase in speed without overheating is then impossible. The limit temperature will be reached at a higher speed only with a sharp increase in the flight altitude, when the density of the air and the heat fluxes, decreasing with the altitude, become insignificant, while the radiative cooling is not varied. The lower "thermal" boundary of the corridor of steady flight is thus established.

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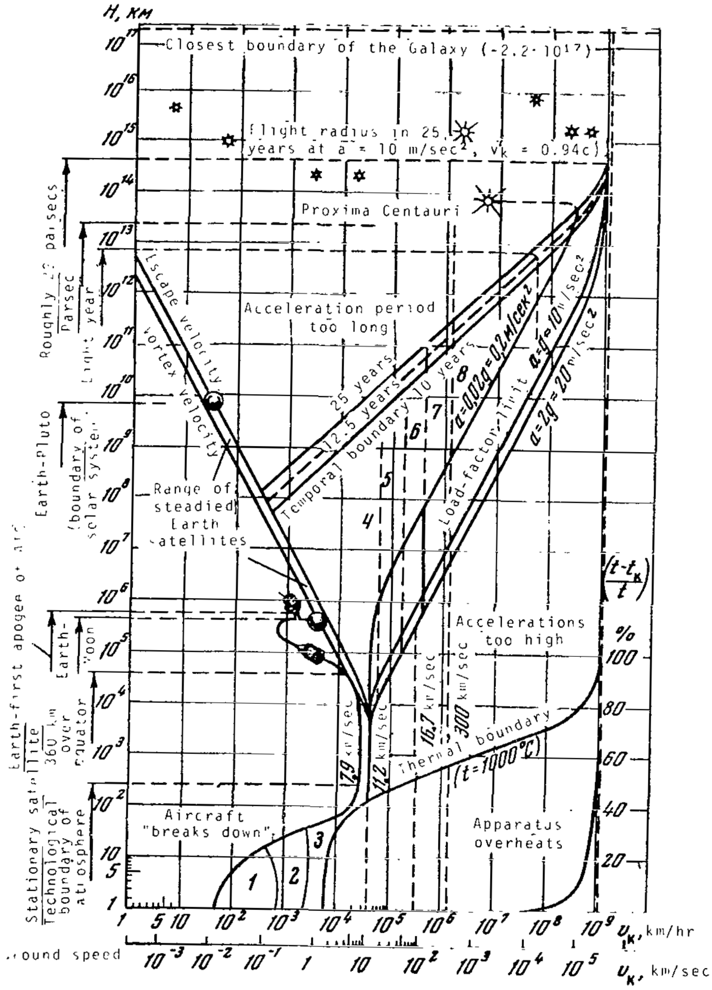


Fig. 3. Ranges of Possible Flight Speeds and Distances Relative to the Earth and Engines Suitable for their Mastery.
(1) Aircraft with Turboprop Engines; (2) Turbojet Engines;
(3) Liquid-Fuel Rocket Engines; (4) Nuclear-Propulsion Rockets;
(5) Electrothermal Engines; (6) Electro-Plasma and Ion Engines;
(7) Ion Engines; (8) Quantum Rockets.

When the flight altitude increases, the speed must be increased, or else the aircraft will "break down", since the air cushion /35
below the wings becomes less dense. Agreeing that the lowest reference pressure is 390 Kg per 1 $m^2$ of the wing, we can find the uppermost "aerodynamic" boundary of the corridor in which steady flight is possible. We should mention that, at low speeds, of all the apparatus heavier than air to the left of the aerodynamic boundary, gliders can glide, while, further to the left, helicopters, caliopters or, for example, flying "platforms" capable of vertical take-off can fly.

The record speed of an aircraft preliminarily lifted to some altitude by another apparatus, the X-15 installed in the USA in 1962, was 6693 km/hour (altitude of about 17 km).

The record speed of an aircraft making an independent flight from the group was made in 1962 by the Soviet pilot G.K. Mosolov, and was equal to 2678 km/hour at an altitude of 34,714 m.

The International Federation of Aeronautics, which records all the world aviation and space records, held that, up to an altitude of 100 km, flights are considered to be aviation-type, and above this, they are space flights.

Flights in the upper layers of the atmosphere at high speeds are particularly important since, during re-entry into the atmosphere of the Earth and other planets at a high speed, the problem of a heat barrier becomes very acute, and this must be investigated very carefully.

Thus, climbing higher and higher toward the ceiling of the atmosphere, we gradually approach altitudes on the order of 1000 km (see Fig. 3), and enter the region mastered by Soviet astronautics. However, having gone so far from the Earth, we cross over the conditional threshold which separates aviation from astronautics. Multi-stage rockets with engines using chemical fuel have allowed us to pass beyond it. They can service the "circulation zone" of artificial Earth satellites and satellites of the Sun, and bring laboratories to the closest planets of the solar system.

After reaching the first cosmic velocity near the ground - 7.9 km/sec - the apparatus goes into the regime of a satellite in outer space, where, on the one hand, the thermal boundary fades away as the atmosphere becomes more rarefied and, on the other hand, the aerodynamic boundary of winged flight disappears, the apparatus should be a rocket which flies out into space solely on the basis of the jet stream of the working medium ejected from the engine.

However, as always in such cases, we can note new boundaries to the regime of steady flight. For satellites, this boundary

corresponds to the so-called escape velocity (near the ground, this /36
is the second cosmic velocity, equal to 11.2 km/sec).

It is well known that, as the distance from the satellite to the center of the Earth increases, its speed of equilibrium, i.e., that at which the satellite moves along a circular orbit, decreases. An increase in the speed above the equilibrium point results at first in an elliptical trajectory, and then in a withdrawal of the satellite from the sphere of the attractive force of the Earth and its conversion into an artificial planet. As can be seen, the speed and altitude range of Earth satellites is relatively small. The speed range of apparatus which pass into outer space is also limited.

Interstellar apparatus can be launched from a satellite-station or from a satellite orbit which has a certain circular vortex velocity, in a way similar to the launching from a heavy satellite of the Soviet rocket-carrier which brought the automatic interplanetary station (AIS) onto a flight orbit toward Venus. The uniform pickup of the apparatus begins at this speed.

Since the pickup rate is limited, the entire region in which the accelerations necessary for reaching each specified speed are extreme drops out. Basically, this "lower boundary" can be graduated, since, when reaching relatively low speeds, the period of the effect of the load factor is shorter and, consequently, the pickup rate can be greater. If, in the case of prolonged pickup, the acceleration, limited by the biological characteristics of the human organism, cannot be taken as more than 20 m/sec, then, for example, it could be doubled in a limited segment in order to obtain a speed of 20 km/sec. However, in a flight to a maximum distance in 25 years at a relatively short time of the pickup stage, this possibility cannot be considered as admissible. Therefore, it is assumed that an acceleration which acts for a long time on the rocket crew should not exceed $a$ = 20 m/sec$^2$. V.I. Yazdovskiy considers that the acceleration of a craft should not exceed that to which man is accustomed - about 10 m/sec$^2$. The corresponding curve is represented in Figure 3.

Thus, in using engines which can produce a high absolute /37
thrust, the pickup rate is limited by the biological characteristics of the human organism (see Fig. 3, ranges 4-6). In ranges 7 and 8, the pickup rate, as can now be predicted, is limited technologically by the acceleration $a$ = 0.2 m/sec$^2$, since ion engines obviously cannot produce greater accelerations, now guaranteeing $a \leq 0.002$ m/sec$^2$.

Let us assume that the total flight period does not exceed the average period of the creative life of a man, i.e., roughly 50 years. The maximum flight radius is then determined as a period of 25 years. The distance which the apparatus and engines of different types seem to be able to span in this time also gives the upper "temporal" boundary. Since all the speeds and distances in Figure 3 are shown relative to the ground, the speeds relative to the Sun and the center of the Galaxy can be shown only conditionally. They are plotted by the dashed line: the third cosmic velocity (in the direction of the rotation of the Earth) is 16.7 km/sec, and the fourth - 300 km/sec relative to the center of the Galaxy - permits the craft to "withdraw" from it to other galaxies of the Universe.

In the range of flight speeds near the speed of light, all the cited boundaries are modified, which becomes noticeable after reaching roughly one-tenth the speed of light.

An examination of the figure again shows that, of all the known engines, only the ion and quantum engines can possibly permit us to go beyond the boundaries of the solar system. The electric rocket-ion engine allows us to go only part of the way to stars during one lifetime. It is probably that only one of the engines now known - the quantum engine - will be able to guarantee a voyage to other stellar worlds.

Moving away from the condition of limited approximation of the flight speed to the speed of light, which was assumed in connection with the colossal difficulties in such an acceleration. we can go into the narrow corridor in the uppermost right-hand region of the graph. This should include the quantum craft, for reaching distant stellar worlds of our Galaxy and, perhaps, other galaxies. The quantum rockets will also predominate in this region, if more effective engines are not found for galactic craft, or /38
basically new methods of bringing man through the endless deeps of the Universe are not discovered.

## Electrification of Space

Wherever the spacecraft is directed, it must have sources of energy for the operation of the engines, for supplying the communication channels, sustaining the life activity of the crew, producing "comfort zones", and for the on-board instruments - navigation apparatus and other systems.

The production of cosmic power units is the key to the conquest of outer space.

The requirements of high reliability and vast reserve at high temperatures and under the high vacuum of outer space (less than $10^{-6}$ mm Hg), when a number of metals sublimate, or "boil off", are imposed on the cosmic sources of electric energy. The absence of or a low force of gravity, the effect of solar radiation and meteorites complicate the operational conditions even more.

A failure of such systems is inadmissible, while a prolonged stop is extremely dangerous.

A guarantee of operation for a number of years without servicing and repairing is a most difficult task. The period of operation without breakdown of most of the modern mobiles systems does not exceed 3000 hours. That is why the reliability, invulnerability and resource become the three "whoppers" on which a system of cosmic power engineering should be based. Low reliability and vulnerability can "bury" systems which are the best in all other aspects.

Cosmic systems also differ from ground power units in that they are "optimized", projected from the condition of attaining the least volume and weight. The latter means that the perfection of a cosmic power system can be evaluated by the specific power - amount of kilowatts generated per kilogram of weight of the system. In computing the specific power, the specific energy of fuel used, the sum of the specific weights of the heat source, the converter, all the auxiliary elements and, finally, the length of the flight, are considered.

How much energy is needed for the "natural needs" of space /39
apparatus?

Most of the unmanned apparatus which fly near the ground require power from several watts (on small communication satellites) to 1 KW during the course of several years. For manned apparatus, the average requisite power is from 0.1 to 1 KW per man. Thus, on the US apparatus "Mercury", a power of 0.26 KW was used to guarantee the life activity of the astronaut. Since convection (natural air movement) does not take place in the astronaut's cabin, because of the lack of gravity, much of this power is spent for ventilation of the cabin.

For the sounding of the Sun and its planets, as well as for flights outside the solar ecliptic, (plane of the orbit of the Sun), systems with a power greater than 50 KW are necessary. For manned space stations and laboratories in the space around the Sun, the required powers can increase up to tens of thousands of kilowatts for operations lasting up to ten and more years, depending on the "population" of the system and the scientific tasks. Finally, the natural energetic needs for a "minimal spacecraft" which can fly to Proxima Centauri and return to the sun should be satisfied for 50-60 years and reach 60 billion KW per 1000 tons of the starting mass.

There are now no universal sources of energy for outer space. The most suitable one should be selected for each range of use.

Chemical, solar and nuclear energy can be used for the power

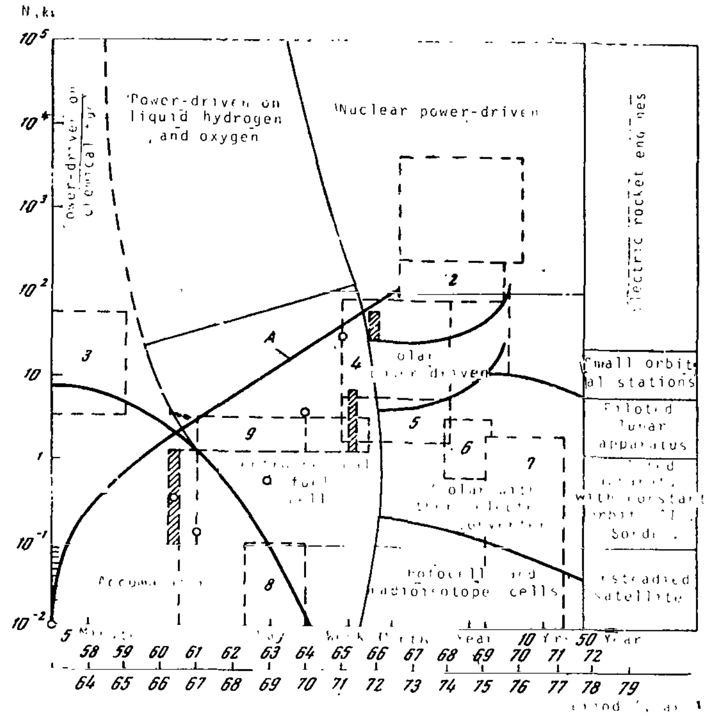


Fig. 4. Ranges of Use of Cosmic Power Systems in Dependence om the Requisite Power and Time of Their Use (The Dotted Line Shows Regions in which Analyses are Being Conducted, and the Small Circles show some of the Devices Which Have Been Designed)
(1,2) Electric Rocket Devices According to the Projected Published; (3) Power Unit of Braking Engine for the Return of the Spacecraft and Crew; (4) Power Station of an Orbital Spacecraft; (5) Electric Station Intended for Flight on the Moon and Return; (6) Communication Satellites (in 1965); (7) Meteorological Satellites (in 1965); (8) Experiments on Smooth Lunar Landing; (9) Return to the Atmosphere of Manned Craft; (A) Upper Boundary of Energy Powers Necessary in the Near Future for the Conquest of Space (the Scale of the "Period Interval" Relates to this Dependence).

system.

Figure 4 shows the ranges of expedient consumption of different types of power stations in dependence on their requisite power and the time of usage.[13]

The ranges of powers necessary for solving different problems in space are plotted along the right-hand vertical scale of the figure. The electric power is plotted on a logarithmic scale on the left-hand vertical rule, and the duration of operations is plotted along the horizontal rules on the same scale.

As can be seen, it is unsuitable to use the regular ground power systems at low powers for more than one day. The use of such an exotic high caloric fuel as liquid hydrogen and oxygen, allows these systems to be "sustained" in space up to one week. In view of the very limited possibilities of using such systems, we will not discuss them further. /41

The fuel cells (FC) included, for example, on the "Gemini" craft can be used for moderate powers. For lower powers and prolonged flights, solar electric converters (SEC), photoelectric and photochemical elements are suitable. For substantial powers and long operations, atomic reactors combined with various devices converting heat into electrical current occupy the suitable position.

Some researchers suggest that nuclear reactors and solar collectors must be used in combination with turbogenerators for high powers and a prolonged time of operation in the upper part of the region situated on the right. For lower power, various thermoelectronic (TEC) and thermoelectric converters are expedient. We should keep in mind that the limits to the cited ranges are actually "blurred", the schemes under investigation partially encroach upon them into "adjacent" flight ranges, in dependence on the experience accumulated, the points of view of specialists, the level of production and the auxiliary tasks of the apparatus.

The dashed line marks off parts of the regions in which experimental studies have been conducted or are being carried out. The points which are not filled in designate projected apparatus.

On the same figure, we see curve A, which characterizes the powers needed in the next ten years, according to a number of

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[13] See SAN Journal, No. 1, 1960.

specialists.[14] The period intervals in the range of years are shown on the last horizontal scale.

Electrochemical Fuel Cells. Fuel batteries or, as they are still called, electrolytic fuel cells, are now being widely investigated. This cell consists of a metallic electrode, hydrogen electrode and electrolyte - salt containing a small quantity of ions of the electrode metal. Alkali metals can serve as the metallic electrodes, e.g., lithium, potassium, sodium, etc. The hydrogen electrode is a porous plate of stainless steel or nickel. The electrolyte divides the metal and hydrogen, not admitting an electron flux, but it brings about the transfer of charges by ions. The electrons separated on the hydrogen electrode as a result of the reaction with ions of the alkali metal pass through the outer chain of conductors, producing useful work equivalent of the chemical energy of the compound of hydrogen and the alkali metal. /42

An increase in the cell temperature brings about an increase in the current due to the increase in ion conductivity.

While the electric energy is being obtained, there is a simultaneous formation of the hydride of the alkali metal, e.g. lithium, which can then be put in the lithium and hydrogen regeneration by heating. The specific output power of the cell is 4-6 W/Kg.[15]

Another type of fuel cell - the oxygen-hydrogen cell - is very promising. The cell is based on the use of the energy of a chemical reaction between gaseous oxygen and hydrogen with an ion-exchange membrane. It is divided into two parts by a membrane or a porous plate. During the operation, the hydrogen is supplied from one part of the membrane, and the oxygen from the other.

The hydrogen electrons break away from its atoms during the electrochemical reactions and fall on the thin metallic electrodes placed in the membrane. These electrons also produce the electric current, which is then supplied to the other side of the membrane.

[14] Stewart, P.A.E." A Comparison of the Capabilities of Electrical Propulsion Systems for Co-Planar Orbital Transfer Missions. Raketentechnik und Raumfahrtforschung, Vol. 7, No. 1, pp. 5-14, 1961.

[15] Here and further in this chapter, the weight, power and other characteristics are given according to foreign data. See: Collection of articles: Preobrazovaniye tepla i khimicheskoy energii v elektroenergiyu v raketnykh sistemakh (The Conversion of Heat and Chemical Energy into Electric Energy in Rocket Systems). Moscow, Foreign Literature Publishing House, 1963.

The hydrogen ions which are formed, passing through the membrane, recombine, and re-unite with the electrons and oxygen. As a result, water is formed from the hydrogen and oxygen, while the energy for its formation, for the "heating" of the hydrogen", is generated in electric form. The reserves of liquid hydrogen and oxygen are on board. One such device was used in 1961 for 50 hours under conditions close to cosmic, with direct current up to 2 KW. As a by-product, these systems produce drinking water (in a quantity of about 0.5 l/KW·hr), which can be consumed during flight.[16] The basic disadvantage of fuel cells is "aging", i.e., a worsening of the characteristics with the time and, consequently, a limited operational time. /43

Source of Energy - the Sun. The Sun emits $0.38 \cdot 10^{24}$ KW continuously. The energy of the Sun can be used in several ways. It can be converted directly into electric current with the aid of the panels of the photocells, as is done on our automatic interplanetary stations. Using "mirrors", or concentrators, we can concentrate the solar energy on a space with the effective liquid which, turning to vapor, revolves the turbogenerator, etc.

Nevertheless, the possibilities of using such atrractive resources of solar energy are limited. To what is this due? First of all, because of the remoteness of the Sun, the energy incident per unit area of the "supplying" surface is low. Thus, at an altitude of 1000 km above the ground, there is only about 1.4 KW per $m^2$ of the surface perpendicular to the solar rays.

It would be desirable for the receivers of the energy to be turned so that their surface faces the Sun. These receivers have several times less area than non-oriented ones for identical output power. This is important, since, for example, the specific weight of the panels of the converting cells together with the wiring is about 45 Kg/KW.

The basic material of the photocells is silicon (iron arsenide, indium phosphate and cadmium telluride can also be used). The cell is similar to a "sandwich", in which the upper thin film of 2.5 is made of a semiconductor - silicon with an admixture of arsenic (layer with electron excess), and a lower thin film of silicon with an admixture of boron (layer with excess of "holes" - electron deficiency). In the absorption of photons on the contact surface, the positive and negative charges (electrons and "holes") go into motion and bring about the arisal of current in the outer circuit.

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16 See: Fuel Cells for Supplying Energy to the "Gemini" Spacecraft. Voprosy Raketnoy Tekhniki, No. 8, 1963.

The requirement of orientation, which permits a decrease in the area of the panels, results in the need for using special directive systems. Although their mass may make up only a tenth of the mass of the collector, the system is nevertheless much more complex in this case, which means that its reliability decreases. Since the solar-energy converters have efficiency up to 10-15% (theoretically up to 25%), their frontal area is about 10 $m^2$/KW. /44

Another disadvantage of the solar cells is that they are subject to the effect of solar and induced radiation. The induced radiation, which is caused by the American nuclear explosions over the Pacific Ocean, has necessitated that additional means be taken to protect the panels of the cells.

Finally, the elements which derive their energy from the Sun lose their source of energy in the shadow of planets, during night on the Moon. Does this not await them when they are installed on satellites which periodically go into the shadow of a planet? What to do in such cases? Nickel-cadmium or silver-cadmium storage cells come to the assistance. However, as is well known, electrolytic cells "don't like" multiple discharging. Thus, for a small number of charge-discharge cycles, the cells weight about 9 Kg/KW·hr. The storage cell usually discharges only 10-15% of its power per cycle. As a result, when there is a large number of cycles, the weight of the storage cells increases up to 100 Kg/KW·hr.

If the satellite completes a large number of loops, while the energy converter is based on the thermal principle, thermal accumulation of the energy of the Sun is more suitable. Thermal accumulators contain a substance with a high latent melting point. For example, lithium hydride melts at 615° and has a latent melting point of 630 Kcal/Kg. We should note that the latent melting point of ordinary ice is almost eight times less. In order to provide thermal energy for a satellite with output power of 1 KW·hr for efficiency of the system of 10%, there must be 14 Kg of lithium hydride.

Various structural designs of the collector-mirrors have been suggested. They include extremely thin nickel films, which weigh 0.5 g/$cm^2$ in all, leaf-type, umbrella-shaped surfaces, plastic inflatable collectors covered inside with a reflecting film. The specific weight of rigid collectors is roughly 0 Kg/KW.

The mirror-concentrators have long been used in southern regions, e.g., in producing boilers, for which a boiler chamber filled with water is placed in the focus of the mirror. Cosmic heliostations are somewhat similar. A steam boiler can be arranged in the focus of the collector; the vapor from the boiler goes to a turbine which rotates the electric-current generator. The excess heat is emitted into space with the aid of a radiator behind the turbine. After this, the heat-transfer agent is pumped into the boiler. During the ground tests under conditions close to those of space, the collector of one of such devices provided up to 0.04 KW per $m^2$ of the collector and could yield 0.065 $KW/m^2$, if part of the power did not have to be used for charging the accumulators operating during the shadow period. /45

However, because of the low energy of solar rays per square meter of the surface, the collector (mirror) of this device is 10 times larger than the area of the radiator behind the turbine. When the collectors are too large, this also limits the powers of such devices roughly by 50 kilowatts. The requirements of the orientation of such devices are stricter than for photocells. A deviation of the orientation system of the collectors from the Sun should make smaller percentages of a degree, which complicates the system to a great extent.

The smoothness of polished mirror surfaces and the transparency of the surface of inflatable mirrors is maintained for more than one year with great difficulties. The erosion by the effect of meteorites (dust) can reach $2 \cdot 10^{-4}$ cm per year. The protons emitted by the Sun can bring about additional erosion of $10^{-3}$-$10^{-4}$cm per year.

The cited disadvantages of the Sun as an external source of energy for spacecraft necessitates that, when the power is increased, the Sun be rejected and the energy reserves be taken from directly on board the apparatus.

Radioisotope and Reactor Power Systems. Radioisotope sources of electric energy and heat, and nuclear-reactor systems, are the most promising in terms of absolute power, specific parameters and reliability. Radioisotope systems are expedient in the range of electric power from tens to hundreds of watts. Single projects have considered obtaining several kilowatts, but they still have not been carried out; therefore, it is difficult to compare them with other sources of energy. /46

Information has been published on the development of several energy sources of this type in the USA. For example, in the system "SNAP-3", which operated continuously for about 2600 hours, the isotope-radiator was polonium-210, which has a half-life of 138 days. The weight of the generator was 2 Kg, and the power was 3.5 W.[17] On satellites of the "Transit" type (USA), radioisotope generators operating on plutonium-238 with power of 2.3 W and 20-25 W were used ("SNAP-3B" and "SNAP-9"). These power systems can work for several years, since the half-life of plutonium-238 is about 90 years.

The Soviet system "Beta-1" has also been described. It has been operated on for a long time as a supply source of the apparatus of a radio-meteorological station. The radioactive isotope

[17] Machine Design, July 22, 1961.

curium-144, which emits β- and γ-radiation during decay, is used in the "Beta-1" system. Its half-life is 290 days.

Isotope generators were used in September of 1965 on the Soviet "Kosmos" satellites as the on-board power systems.

Semiconducting storage cells are used in the cited power systems in order to convert heat into electricity. The efficiency of such converters is 2.5-5% in all. The economy of the system can be increased by using the conversion of heat.

Depending on the space task imposed, the working life of radioisotope power stations may last from 3-6 months to several years.

The basic advantages of the radioisotope power systems is the high energy capacity, simplicity and reliability, small size, the possibility of using some of the heat which is not converted into electricity for auxiliary needs, the possibility of a long working life in using a "long-lived" isotope.

Their basic disadvantage is that the energy release cannot be controlled: the intensity of the decay of an isotope decreases gradually and the energy release therefore decreases with time. Moreover, on a spacecraft, there must be protection of the apparatus and crew from nuclear radiation. Emitting isotopes require /47
minimum protection: for example, polonium-210, plutonium-238, curium-242 and curium-244.

For the most powerful sources of energy, it is more expedient to use power systems with fission reactors which use uranium-235 and plutonium-239 as the fuel.

The first power reactors intended for space, the "Romashka" (USSR, 1964) and the "SNAP-10A" (USA, 1965) used uranium-235. In both systems, heat is converted into electric current with the aid of semiconducting thermo-generators; however, their designs are different. The "Romashka" system represents a reactor-converter. The chain reaction of uranium fission in the active zone of the reactor results in the warmup of the disks of the fuel elements, made of uranium dicarbide, up to a temperature of about 1800° C. Spreading in a radical direction, the heat passes through a cylindrical neutron reflector made of berylium. Semiconducting storage cells made of a germanium-silicon alloy are attached to the berylium reflector. There is a temperature drop during the passage of the heat along the thermopiles of the storage cells, and an electromotive force is formed as a result. A great amount of the heat is emitted from the developed outer surface of the system, since the only method of driving off the excess heat into outer space is emission.

As was reported at an address of the Institute of Atomic Energy imeni I.V. Kurchatov at the Third Genevan Conference on the Peaceful Use of Atomic Energy, the "Romashka" system developed a power of about 500 W for a current of 88 a. The characteristics of the system changed little in time.

The "SNAP-10A" system has a more ordinary design. The reactor heats a liquid-metal alloy of sodium with potassium, which transfers the heat to the semiconducting converter positioned outside the reactor. The power of the system is 500 W. The need for producing the critical mass of uranium-235 and critical size of the reactor, as well as the need for protection from radiation, determine the disadvantageous weight characteristics of the reactor system at low powers (about 1 Kg/W of electric power). These characteristics can also be obtained in using a radioisotope power station. However, when the power is of several kilowatts, the reactor systems are better in terms of the weight data, while, for powers from tens to thousands of kilowatts and long working /48 lives, they are more suitable than others for obtaining the energy on board the spacecraft and, in particular, for supplying the electric jet engines. For more powerful systems, it is apparently necessary to use a turbodynamo system of converting the heat into electric current or a direct conversion in thermoelectronic (thermal-emission) or magnetohydrodynamic converters.

The thermoelectronic cell consists of two plates - hot (cathode) and cold (anode), divided by vacuum or a rarefied ionized gas. If the temperature of the cathode is sufficiently high, the electrons are ejected (emitted) from its surface, move toward the anode, and return to the cathode through the loader on the circuit where the power is released. A cathode temperature of at least 1200° is necessary for operating this system. The need for reducing the space charge of the electron cloud arising between the electrodes, which prevents further yield of electrons, produces additional difficulties. It is also difficult to provide high-temperature insulation. In order to decrease the electron cloud, the gap between the electrodes of the vacuum device should be made very small, on the order of 20 microns. It is an extremely complicated task to produce and maintain such a gap during the operation of the heating element. Another method of "fighting" against the harmful effect of a space charge is to fill the space between the electrodes with a slightly ionized gas, for example cesium vapor. In this case, an ion cloud neutralizing the electrons is produced. The gap can be increased in this respect. However, there are problems of the difrusion of electrons is the ionized medium and the corrosion of the materials when there is cesium. The specific weight of the system is much lower, while the efficiency is higher, than for thermoelectric generators, since the cathode and anode are divided by a space, and an uneffective heat flux can pass through only because of emission.

Atomic Power Station in Space. The machine-less methods of converting heat into electric current correspond more to the direction of technical progress. Any mechanical converter appears outdated when compared to them. However, let us remember that the first atomic power stations operated on the basis of steam technology mastered on ordinary heat and electric power stations, while the first automobiles had steam engines. Obviously, this is one of the regularities in the development of technology, the realization of new discoveries. They first develop more successfully on the basis of the technical topics, materials and technology already mastered. Only in time do new discoveries acquire the technical forms corresponding to them. Turbogenerators are attractive in that they have been investigated and mastered. A mechanical converter - a turbogenerator system - does not differ in scheme from a ground power station. However, a flying power station should be compact, light and capable to operate without repair for at least one year (10,000 hours). The new range for application also presents a number of new tasks for the "old" devices. /49

Vibrational and gyroscopic effects, and wear, which are characteristic of revolving systems, decrease the advantages of mechanical converters for space power stations. However, such systems are presently being used widely.

Some researchers consider the thermoelectronic converter combined directly with a reactor to be more promising.

In the future, after temperatures on the order of 2300° have been mastered in reactors, magneto-hydrodynamic generators (MHDG) could become suitable for prolonged usage. This device represents an electron generator with a gaseous conducting rotor. Such systems were suggested in 1936 by the famous Soviet scientist G.I. Babat. In this system, a high-speed plasma flux (for example, argon or mercury with an admixture of cesium, which provides the requisite conductivity) intersects the magnetic field at a high velocity, inducing the electric current.

In addition to the linear MHDG's, vortex ones have also been proposed, where the gaseous rotor-vortex, revolving, intersects the magnetic field and generates the electric current.

Apparently, this MHDG could be suitable for very high powers. It was reported in the foreign press that experimental systems with output capacity up to 1000 KW have been constructed and tested in a number of laboratories.

Regardless of the type of converter, the atomic power station consists of three basic parts. In a nuclear reactor, the energy is converted into thermal form. Therefore, a reactor with a shielding screen which preserves the system and cabin of the crew from nuclear irradiation, makes up the principal part of the system. The second part, or that which converts the thermal energy /50 into electricity, depends on the selected physical process of conversion. Its mass is small, but, depending on the efficiency, the converter can have a great effect on the principal masses, or the reactor with the protection and particularly the radiator.

The third and most cumbersome part is the radiator. Here, because of the radiation, which is proportional to the fourth power of the temperature, the "excess" heat is ejected into space; the heat is determined by the efficiency and capacity of the converter.

The higher the temperature of the radiator, the smaller and lighter the radiator, but the more the heat is ejected and the lower the efficiency.

## Man in Space

Speaking of the program of mastering outer space and the possibilities of realizing it, we assumed that a manned craft was sent on interstellar flights. This affected the selection of the acceleration rate and the maximum target of the apparatus.

With the greatest amount of processed information, the human brain, equipped with modern apparatus, as a means of cognition, still has the greatest compactness and the best weight characteristics compared to other complex "technological" media. V.I. Parin wrote that the living "computer", or the human brain works continuously all through life, being distinguished by its startling reliability and stability. The brain is very portable, protected by the cranium from interference and mechanical shocks.

The technical analog of the human brain made of semiconducting details, which corresponds in number of artificial cells-neurons to the number of brain cells, should today have a volume of top and base of 10 x 10 m and height of 100 m. The total quantity of radio tubes and transistors now existing on the ground does not /51
exceed the amount of neurons in one human brain. While the brain requires only several tens of watts, its mechanical analog would require several millions of kilowatts for supply. However, in order to obtain full yield from a human, we must produce the life and working conditions to which the crew is accustomed for adjusted cosmic existence.

Particular difficulties arise in connection with the need for protecting the cabin, the equipment and the astronauts from cosmic particles, solar radiation, the emissions of the energy source of the craft (if nuclear processes occur in the source) and other effects. A passage beyond the Earth's radiation belts is connected with complex maneuvers. Showers of cosmic particles can bring about the need for constructing cabins - shelters from increased radiation. All this ultimately leads to an increase in the weight of the craft, which means difficulties in designing it.

"The human organism", V.I. Yazdovskiy said figuratively, "is like a semi-liquid drop in a loose shell. This drop is kept with difficulty within certain boundaries of the bone and muscle...even when at rest, but with the head upside-down, man cannot live. In general, when Adam was 'created', this should have been written on his back: 'handle with care, do not shake, look out!'".

However, man yields easily to training, becomes successfully adapted to unusual conditions and, using the achievements of science and technology, creates for himself the suitable conditions, the acceptable "microclimate". In order to produce such conditions in space and on the way to it, we must solve a number of most complex medico-biological problems. Let us discuss some of them which determine the technical characteristics of spacecraft.

As is well known, constant movements do not affect the human organism. Only the forces which bring about a change in velocity act on it.

The take-off of a spacecraft from the Earth, as well as its deceleration during re-entry, are connected with substantial accelerations, and changes of the velocity in magnitude and direction. /52
This is accompanied by the action of forces which cause and determine the magnitude of the load factor on the aircraft and the people in it, i.e., the ratio between the power with which the body presses on the support and the weight of this body under ground conditions.

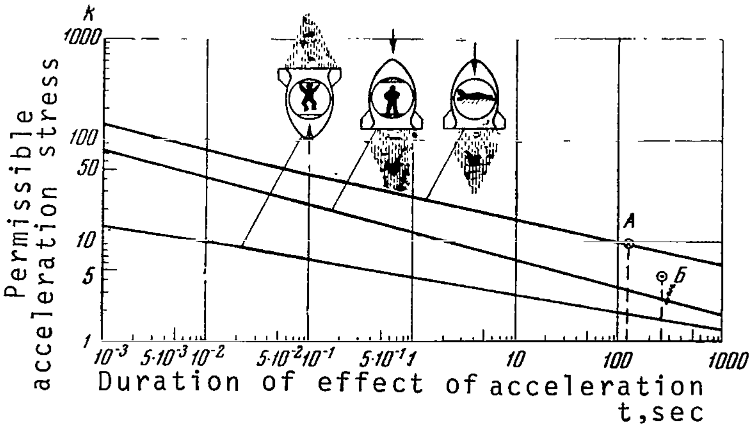


Fig. 5. Permissible Acceleration Stresses and their Possible Duration in Dependence on the Position of the Man in the Rocket. The Directions of the Effect of the Acceleration Stress are Shown by the Arrows.

The experience accumulated in aviation technology indicates that the greatest stresses which a man can endure without injury to his health depend both on his position in the craft and on the duration of the effect of the acceleration stress. This can be seen from the graph presented in Figure 5. Obviously, the organism endures a transverse load much better than a longitudinal one. It endures longitudinal loads directed from the foot to the head particularly poorly. A triple acceleration stress of such a type can last only 5-7 seconds without injury. An acceleration stress in the ordinary direction of the effect of weight - from the head to the feet - is sustained in a better manner, and an acceleration stress directed across the human body is endured even better. This occurs, in particular, because the heart does more work during the effect of an acceleration stress across the body in order to lift the "heavy" blood to the necessary height. If the man is lying down, the acceleration stress acts across the body, the height to which the heart must "lift" the blood is less, and it copes more successfully with its task.

There are data in the foreign literature which show that acceleration stresses repeated ten times $k$ = 10 are endured by humans for $t$ = 120 sec (point A in Fig. 5). Using these data, it is easy to compute the velocity imparted to the rocket in this time: /53

$$v_{\text{к}} = kgt = 10 \cdot 9{,}81 \cdot 120 = 11770 \text{ м/сек} \approx 11{,}8 \text{ км/сек}.$$

Thus, in two minutes we can gain the velocity which is sufficient for entry into interplanetary space. If we assume that the acceleration stress is repeated five times, then, in order to obtain a velocity of 11.8 km/sec, we must increase the pickup time by a factor of two. In this case, the acceleration stress is below the permissible value (point B on Fig. 5). However, the more intensively the rocket is accelerated, the less time its engine will use, in the climb, the still unburnt fuel and the still unused stages in the field of gravitation of the Earth. The acceleration tempo is limited by the biologically permissible acceleration stresses.

Actually, the acceleration stresses will change during acceleration from zero to the extreme values, and a computation is more complicated compared to the calculations presented.

A selection of the ratio between the length and the magnitude of permissible acceleration stresses is presently being made with success and will be made more specific later, in the process of designing habitable satellite-stations.

For "minimal" stellar flights starting from satellites, very low constant accelerations will probably be characteristic. The conditions on them are close to most of the modern apparatus which move a great part of the way with disconnected engines, which means without accelerations. In order to restore even some of the "weight" of the crew, special methods may be necessary there.

Only in the very distant future will the problem of acceleration with maximal acceleration stresses again arise for apparatus with practically unlimited power potentials, as for the modern rockets launched from the ground.

Since insignificant accelerations, which mean low acceleration stresses, may be characteristic for spacecraft crew in the foreseeable future, let us discuss the problem of the effect of weightlessness on the human briefly, which problem was first studied in 1876 by K.E. Tsiolkovskiy.

For an apparatus withdrawing from the Earth, its attraction /54 practically ceases to act even at a distance of 1 million km, while, since the gravitation fields in interstellar space are neglibible, all the bodies in it seem to be in the position of so-called static weightlessness when there are no accelerations.[18]

However, a weight loss does not mean a loss in mass. The inertia of the bodies remains, which means that, in order to change the velocity of the craft, it is always necessary to apply a tractive force to it.

Experiments show that preliminary training permits most people to quickly become familiar with the conditions of weightlessness.

Yuriy Gagarin reported that, after the onset of weightlessness, he did not feel anything upleasant. It was important to find whether or not one can become accustomed to longer stays under the conditions of weightlessness. German Titov spent twenty-four hours under such conditions and felt in good health. Then Andrian Nikolayev and Pavel Popovich stayed four and three days, respectively, in outer space. Their multiple-day flight allowed us to study the effect of weightlessness and other factors of an orbital flight simultaneously on two astronauts and to compare these observations. It was first found that the twenty-four-hour period of physiological

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[18] In the case of movement along a circular orbit at a velocity, for example, of about 8 km/sec, when the centrifugal force becomes equal to the attractive force of the satellite continuously "falling to the ground", the weight loss is due to the satellite's velocity and is therefore called dynamic weightlessness.

processes takes place satisfactorily under the conditions of such a flight. Valeriy Bykovskiy was under the conditions of weightlessness for five days and felt in excellent condition. Finally, after special preparations due to the anatomical-physiological characteristics of the female organism, Valentina Nikolayeva-Tereshkova completed a three-day space flight. According to the plan, it was suggested that the duration of her flight would be one day. However, the satisfactory condition of this astronaut allowed that the flight be lengthened to three days. The Soviet astronaut Leonov and the American astronauts White, Cernan and Collins walked from their craft under the conditions of weightlessness into outer space and worked there.

These flights, as well as the flights of American astronauts, permitted us to obtain encouraging results on the penetration of man into the situation of a space flight and, in particular, the /55 conditions of weightlessness. However, much still remains to be done in the study of the problem of weightlessness. It is not clear whether or not any man will become accustomed to weightlessness under the conditions of a many-day, many-month flight. Thus, US specialists consider that roughly half the population will find the absence of weight pleasing, one-fourth will have an indifferent reaction, and the remaining fourth will not be able to adapt to this state.

There are indirect data that disorders can arise in the cell division of the bone marrow, where the elements of the blood are formed, under the conditions of prolonged weightlessness.

We should mention that, before developing the necessary skills to simplify the movement of people under the conditions of weightlessness, it will be possible to use magnetic footwear, rubber sucking disks, gas motor-nozzles and other like media.

In our opinion, even if man is found to be capable of adapting completely to weightlessness, he can stay under the conditions of weightlessness only for relatively short flights (maximum of several months). The fact is that the human musculature needs systematic training. If methods for such a training can be thought up for the "external" muscles, for example using resin gaskets, etc., then the muscles on which the internal organs of the man are "suspended" will be difficult to strain under the conditions of weightlessness. Let us remember that, after a man has been lying down for several months during an illness, he must learn to walk again. Injured muscles undergo atrophy relatively rapidly, etc. This means that artificial weightiness will have to be produced during prolonged flights.

If the engine thrust is insufficient for imparting continuous acceleration (retardation) to the craft to produce the necessary induced weight, or if a flight trajectory on segments of which

the engine is disconnected is selected, then, as K.E. Tsiolkovskiy showed, induced weight can be produced by uniform rotation of the cabin of the craft around the longitudinal axis. In order to obtain an acceleration of the force of gravity corresponding to that on the ground, it is sufficient to move the cabin 4 rpm on the "rim" of the habitated cabin made, for example, in the form of the torus /56
of a "boublik", with radius of rotation of 60 m; with a radius of 15 m, the velocity of rotation should be increased to 8 rpm. However, it has been shown in a number of publications that, with this number of revolutions, signs of sickness are already observed. Therefore, the radius of rotation should exceed 15 m.

As for the weightlessness, it will occur during separated flight segments, when the rotation of the cabin must be stopped for some reason, as well as in cases of a breakdown with the system producing artificial gravity.

Turning to the effects of interstellar voyages on people, we must keep in mind that the first such flights, which are connected with separation not only from the Earth but also from the solar system, the unusual character of the voyage, the forthcoming discoveries, will produce a unique psychological state on the part of the crew. Since the crews of such craft will be relatively small groups, specialists are developing methods of selecting the crew members according to their psychological compatability, as well as according to the nature of the work to be carried out by each astronaut during the flight. It is encouraging that such voyages will be made by people who have already mastered the space around the Sun and who are incomparably more prepared for an interstellar voyage than we are today.

The first successful experiment of forming the crew for a spacecraft was set up by Soviet scientists during the flight of "Voskhod". Its commander Vladimir Komarov, the scientist Konstantin Feoktistov and the doctor Boris Yegorov carried out most important observations jointly.

We should mention one more problem - the need for providing nourishment and rest for the astronaut. As is well known, this problem has been solved successfully when men stayed in outer space for several days. However, as the duration of the flight is increased, the problem becomes more complicated.

As is known, every man requires roughly 770 Kg of water, 320 Kg of oxygen, and 300 Kg of organic matter every year. Since there will be at least a few people in the crew of the spacecraft, the requisite oxygen and food supplies will become unportable. Only one way remains - take with them only emergency supplies, and pro- /57
duce the rest on site.

In designing a longer-range and, in particular, a galactic craft, a complete physico-chemical cycle of matter must be provided in it. K.E. Tsiolkovskiy suggested that greenhouses be produced on the craft - the vegetable world of these microplanets. An animal world could also be added to it.

A study of a unicellular alga - the chlorella - showed that, in using carbon dioxide, it can serve as a unique oxygen plant. A liter of a suspension of chlorella discharges 10 liters of oxygen in one day. It consists of one-half full-valued protein, 25% fats, 15% carbon, 10% mineralized salts, vitamins; the chlorella reproduces with exhausting rapidity. It will probably be the non-ground satellite of the astronauts.

Small animals which live on chlorella and fodder cultivated in a greenhouse will be able to provide the necessary amount of animal proteins for the astronauts.

A.A. Nichiporovich emphasized that we presently have the knowledge, organisms and techniques which will permit the production of a closed cycle of matter to be used in the not-too-distant future and further perfected.

## 2.

## IN THE SPACE AROUND THE SUN

### Islands of Intelligence on the Shores of the Planet

The first region of outer space which was mastered was the space around the Earth. On October 4, 1957, a Soviet artificial Earth satellite, the first in the world, called the "Miracle and Symbol of the 20th Century" was put into orbit. This event, or entry into outer space, necessarily affected all the branches of science and further development of the practical activity of humanity. /58

The first satellite completed about 1400 revolutions in 92 days and flew 60,000,000 km in space around the Earth. Today, artificial satellites of very different types fly above us. Artificial satellite technology has made great progress from the first, which weighed 83.6 Kg, to the first space laboratory Proton-1, which weighed 12.5 tons.[1]

As K.E. Tsiolkovskiy predicted at the beginning of this century, the space around the Earth, the shores, the "edge of the Universe", is becoming the leading edge, the spring-board for assault of outer space. The number of artificial Earth satellites put into orbit increases continuously. They allow us to carry out prolonged and systematic observations of the space surrounding us.

All the artificial Earth satellites[2], both constructed and planned, can be divided into 4 types in terms of designation and size: Small automated orbital satellites; controlled and manned satellites, which climb to an altitude of 100-150 km with 1 or several astronauts on board; spacecraft (manned satellites) on stationary and variable orbits which return to the Earth; interplane- /59

[1] See: Izvestiya, August 15, 1965

[2] This division of satellites can also be used for the satellites of other planets.

tary laboratories and stations of the stationary type with a crew, which are sent into orbit and connected with the Earth by cargo rockets.

Other types of satellites can also be designed.

As is well known, K.E. Tsiolkovskiy suggested the first design for an artificial Earth satellite. Since then, various artificial satellites have been described repeatedly in general outline in scientific and science-fiction literature. The next "burst" in the number and depth of such developments took place in the 50's on the eve of man's entry into outer space. In this case, significance is given to space laboratories, from those in which several researchers could sit to a space city with population of 20,000 people, as proposed by D. Roumik.[3]

Recently, the designs of satellites are being based more and more carefully on technology, and their cost and economy of operation are being analyzed. In examining the possibilities of a design, the existing or projected rocket apparatus, the parts capable of going into orbit and units of future Earth satellites are considered. Based on the results of space data accumulated, the first television transmissions from space, successful radio relaying, and particularly the results of the flight of the first 10 astronauts and the existing satellites, specialists are attempting to find a definition for future designs. In any case, the designing of at first small, and now very large satellites has ceased to be the occupation of amateurs in astronautics, and has become the occupation of specialists. In this regard, they can analyze in greatest detail those units and systems whose design has been treated by a certain amount of accumulated scientific data and, in particular, practical experience. These include the crew cabin, the life-support systems, /60
engines and systems relaying radio and television transmissions.

It would now be necessary to construct a huge catalog in order to classify and describe the numerous projects published in the Soviet and foreign press. To give the reader a first glance at the level and trends of artificial satellite design, we will discuss three designs of specialized satellites while we investigate the general concepts concerning their construction. We will not discuss all the known purposes of satellites in as much detail. The curious readers can find a vast amount of literature treating this.

Thus, we will list some of the prospects of using artificial

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[3] A description of a number of artificial satellites is given, in particular, by A.A. Shternfel'd [Iskusstvennyye sputniki Zemli (Artificial Earth Satellites) Gostekhizdat, 1956] and B.V. Lyapunov [Isskusstvennyye sputniki Zemli (Artificial Earth Satellites). Voyenizdat, 1963].

Earth satellites and show their basic advantages.

Navigation Satellites. Radio beacons installed on satellites should send guiding radio signals for ships, aircraft and submarines. These signals can be used in the very worst weather, since radio waves pass through rain, clouds, and fog. This satellite is not just one more reference point in the sky. It is producing basically new and precise navigation media.

According to the data published in the press, the position of a craft can be determined according to the radio signals of a satellite with an accuracy up to several hundreds of meters. Satellites also specify and "adjust" all the other navigation apparatus on board the craft.

Weather-exploring Satellites. Thousands of specialists and automatic devices on the Earth are watching the weather today. However, large amounts of space--oceans, deserts, polar regions--still remain blank spots in meteorology. All of these regions are accessible to artificial Earth satellites.

With some artificial satellites, we can approach, in a qualitatively new way, the study of the structure of the atmosphere and temperature processes occurring in it; we can rapidly obtain information on the state of the atmosphere on a planetary scale, and we can compare simultaneous observations from below-- from the Earth--and from above--from the artificial satellite. Satellites and meteorological rockets yield new and most valuable data on the pressure, density, temperature and wind velocity over different altitudes. /61
For example, new cyclone centers were detected with the aid of the U.S. satellite "TIROS-1"[4]. Satellites also allow us to construct a global picture for the distribution of clouds, temperature, reflected solar radiation and natural radiation of the Earth. This information is obtained on satellites with the aid of long-range cameras, as well as with measurements of the reflected solar radiation (in the range of 3-40 μ). The most reliable determination of the temperature of the Earth's surface and the upper cloud boundary is obtained in the so-called "atmospheric window" (7.5-13.5 μ).[5] We should mention that much remains to be done in order to specify the geographic tie-in of observations from satellites and units of a meteorological apparatus.

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[4] The name "TIROS" comes from the initial letters of the satellite program "Television and Infra Red Observation Satellite".

[5] See Boldyrev, V.G.: Using Satellite Radiation Measurements in a Symoptic Analysis. Meteorologiya i Gidrologiya, No. 10, 1962

The artificial satellites "inhabited" by specialists, as well as ground stations and meteorological rockets, increase the efficiency of satellite meteorology even more. The "solar survey" will be widely developed on satellites and stations: the very nature of events on the Sun determines the weather of the Earth.

Computer technology will guarantee a precise weather prediction and will serve as the basis for further development of a new science--space meteorology. Long-range and detailed weather predictions will be used in time for active weather control.

Satellite-transmitters and Relays. We have already become witnesses to the first television program transmitted from Soviet spacecraft and television transmissions from the USA to Europe carried out with the "Telstar" satellites ("television star"). We have seen television transmissions from the Far East through our relay satellite "Molniya-1".

Today, when cooperation between many countries is being vigorously developed, increasingly high requirements are being imposed on communication systems. The launching of artificial satellites has opened up new prospects in using ultrashort waves for long-distance communication. The apparatus of satellites can be used both for transmitting a report on events taking place in outer /62 space and as a passive or active relay of telecommunications on the Earth.

Today, there are millions of people in the television "viewing room". Very soon, because of relay satellites, a number of which began with the "Echo" satellite[6], a unique mirror in outer space, which returns the radio signals incident on it to the Earth, will introduce billions of viewers to this room, as well as tens of television programs. Even alone, this is sufficient to justify the studies on artificial Earth satellites.

For uninterrupted communications, there must be such a number of satellites on orbit that one of them is always within the field of vision of two ground stations, which maintain communications among themselves.

For world-wide television, it is particularly convenient to use satellites positioned uniformly on a so-called stationary orbit, i.e., lifted to an altitude of about 35,800 km over the Earth and arranged on the plane of the equator.[7] In this case we can

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[6] The first relay satellite in the international space research program (with the participation of the USSR).

[7] Professor P.V. Shmakov carried out calculations which concerned the possibilities of television broadcasting using such relays.

manage with three artificial satellites in all. At this distance, a satellite has the same angular velcoity of rotation as the Earth and, thus, "hangs" over that point of the surface where is was "suspended". So that this satellite will not "slip" from a given site, a correction should be made with the aid of special engines, of which we will speak below.

Specialists are assuming that systems with the satellites will soon become more economical than all other long-range systems.

Cosmic televisions systems strengthened the connections between different peoples. Scenes of all the theaters of the world, all the stadiums, museums halls, prominent architectural monuments and and landscapes of any country will become accessible to television. At the same time, people will be able to observe the flights of rockets and spacecraft, and, finally, look at the landscapes and reference points on other planets of the solar system. They will /63 see researchers and scientists landing on them with their own eyes. There will be remarkable lessons in astrography. A manned satellite with a transmission center can be called "a Sun of information which never sets". Transmissions seem to carry each man onto a satellite, so that he can hear and see the entire planet.

Space television will help the pilot-astro aut, the most important space explorer who will storm the planets of the solar system, not to feel alone and separated from the Earth.

Figure 6 shows one of the perspective communication satellites[8], in the design of which the solutions which were validified on artificial satellites and which have already operated in space were used.

The satellite has two independent sections. The electronic apparatus is installed in one, and the power system, equipped with a nuclear reactor, is in the other. There is a greatest possible distance between the sections so that the effect of the reactor's radiation on the apparatus is decreased.

The satellite is equipped with an electric rocket power plant which provides a specific thrust of 2000 Kg.sec/Kg. This plant has 12 exhaust nozzles and guarantees that, in 75 days, it will be transferred from the preliminary low orbit, where it is brought by a liquid-propulsion rocket engine (LPRE), to a synchronous stationary orbit. (35,800 km above the Earth), and to move the satellites in any direction and stabilizes it in any position. The weight of the section with the electric rocket power plant and the reserve of working fluid is 1215 Kg.

[8] See: Karman: JAS Paper, No. 192, 1962.

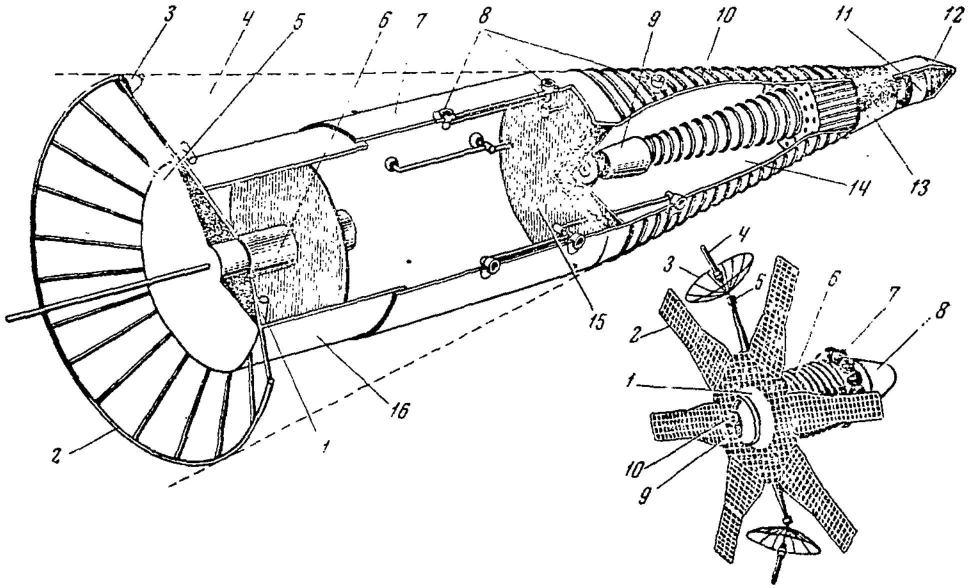

Fig. 6. Communications Satellite
On the Left--one of the Prospective Satellites: (1) Horizon Locator; (2) Antenna; (3) Solar Tracking System; (4) Cone of Shadow Protection; (5) Transmitter of Heat from Equipment (Payload); (6) Relays, Communication and Navigation Equipment; (7) Container into which the Section of Payload and Antennna is Drawn During Takeoff; (8) Nozzles; (9) Energy Converter; (10) Transmitter of Power Section; (11) Nuclear Reactor; (12) Shield; (13) Guard; (14) Power System; (15) Tank of Working Fluid; (16) Payload Section (Opened). On the Right--Satellite "Molniya-1"; (1) Pressurized Capsule; (2) Solar Battery; (3) Pencil-beam Antenna; (4) Antenna Orientation Transducer to the Earth; (5) Homing Antenna; (6) Radiator-Cooler; (7) Reserve of Working Fluid for Micro-correction; (8) Correcting Motor Apparatus; (9) Orientation Transducer for Corrections; (10) Solar Orientation Pickup.

/64

The payload section has a communications system with a transmitting station of 10 KW power, consisting of 4 relays and two units supplying the parabolic antenna. Moreover, the navigation /65 equipment is also situated in this section. There are two transmitters on its surface; one of them, with area of 30 $m^2$, ejects the excess heat released in the electron tubes (around 30 KW), keeping the temperature at a level of 150-200°; the other, with area of 18 $m^2$, allows the temperature of single elements in the electronic apparatus to be decreased to 70°. The payload is 75 Kg.

The total weight of the satellite during flight on the preliminary orbit is 3765 Kg, and that on the final stationary orbit is 2730 Kg. The satellite is oriented so that its bow is directed toward the Sun while the antenna is directed toward the Earth. The excess heat transmitters consist of numerous types welded directly onto the surface of the satellite. This transmitter design is most resistant to meteorites and, moreover, increases the rigidity of the satellite envelope. To increase the reliability of the communications system, it is suggested that there be two satellites for each of the three ground stations, while three artificial Earth satellites are sufficient for relaying over the entire surface of a planet from a stationary orbit.

Each of the satellites has three communication channels which guarantee the work of 27,000 2-way television channels. Constant orientation of the satellites with the nose toward the Sun is guaranteed by a practically tangential passage of solar rays in relation to the heat transmitters; thus, the best heat transfer is guaranteed.

Artificial Satellites--AIS. Three stationary satellites with crews will be constructed in time. There will be systems which provide communication with the Earth's inhabitants on each of them. These satellites will serve as world-wide telephone stations. We will be able to talk over the telephone to any point on the globe. A single portable transistor radio should be able to send special signals to some regional station. It will direct them to a local relay connected with the satellite. The signals from the satellite will be transmitted by the corresponding station on the Earth, from there to the city station, and finally to the suscriber.

Satellite--Observatories in Space. Telescopes and radio telescopes installed on satellites will help astronomers to avoid atmospheric interference. Physists will also be able to use a larger number of instruments for direct observation beyond the atmospheric boundaries. A "pure" cosmic sky is being opened up to scientists. /66

Radio telescopes will be able to catch signals coming from huge distances without atmospheric interference. Telescopes and radio telescopes of larger sizes than those on the Earth will be assembled under the conditions of weightlessness. Large exposures will be used in photographing objects because of the lack of a "swaying" atmosphere. Moreover, their brightness will increase against the black cosmic background. All this raises the observers' potential. For example, if a large telescope with objective of 2 m in diameter or more is installed on an artificial Earth satellite, it will be possible to observe giant planets revolving around the stars which are close to us.

Satellite--Moons. A light reflector concentrating a light flux will guarantee the illumination of a single region of a planet during the shadow part of the day. In order to obtain that illumination which the full Moon gives on a cloudless night, there must be a projector that has a mirror with diameter of several hundreds of meters. The illumination can be increased by superposing the beams of several projectors.

Satellite--Information Storehouses. A great deal has been written about space people who supposedly left their marks on the Earth. In our opinion, such findings are impossible. It is practically impossible that traces were left by coincidence, and it is illogical that they were left on the Earth in particular. The fact is that only carefully "conserved" information could reach us. However, it would be just as unintelligent to "conserve" information on the surface of the Earth as to leave it in the bay of a bubbling volcano. We know that many civilizations on the Earth have been destroyed with practically no trace as a result of wars and natural and geological catastrophes; valuable libraries have been burned and unique architectural masterpieces and sculptures have been destroyed.

On the other hand, stable satellites protected from meteoritic erosion obviously could remain reliable information storehouses. The planet could serve as beacons for determining the location of this storehouse. Was this not the origin of the satellites of Mars proposed by I.S. Shklovskiy?

Satellite--Orbital Maintenance, Booster and Servicing Station in Space (OMBS). The establishment of man in space and his penetration into its depths will take palce much more reliably after there are OMBS in the space around the Earth, after the problems of docking orbital spacecraft are solved, and after the questions on mooring craft to a space station are answered. These problems are now being successfully solved. Complex satellites and complex apparatus of a very different type can be hooked up and repaired at a space station, to which they are conveyed in parts. Reserves of groceries, fuel, medication, mechanical units, etc., concentrated on the station, will expand our potentials and increase the reliability of all the systems used for space research. /67

The time for the construction of large stations in space is at hand, and the corresponding problems are now considered with all the carefulness possible. For this purpose, we must obtain and

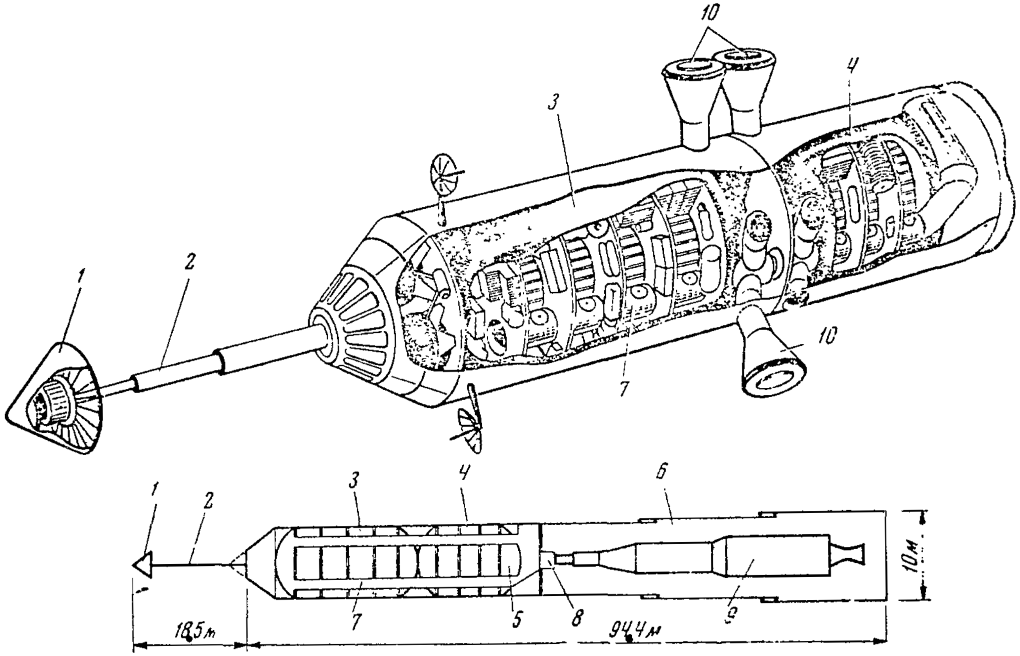


Fig. 7. Launching Station Design (OMBS)
Above--General Appearance; Below--Component Diagram: (1) Nuclear Power System; (2) Telescope Rod; (3) Laboratory; (4) Airtight Section for Launching Service with Control Equipment for Testing and Repairing the System; (5) Section for Maintenance Work; (6) Three-Section Telescopic Hanger in Open Position; (7) Tunnel for Movement of Crew; (8) Mechanism for Putting the Hanger Along the Axis of the Space Station; (9) Servicing Space Craft; (10) Apollo Spacecraft Attached to the Output Drums of the Station.



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think over a large amount of information on the behavior of materials and people in outer space.

The construction of one of the American OMBS variations (Fig. 7) is proposed to start by placing the first section, a laboratory weighing 100 tons, in orbit. In the second stage, it should be equipped with another 100-ton section, guidance and launching devices, and then equipment for assembling the space apparatus. The crew consists of 25 people (10 for command, and 15 researchers) and is put in orbit after each of the sections is orbiting reliably.

A small rocket should be included in the complex of the station for towing details during the assembly work and for conveying the crew. The suggested height of orbit of the station is 550 km, and the angle of inclination to the Equator is roughly 40°.

The station should have a power plant with capacity of 30 KW, which guarantees the electric power necessary for the crew and for all the studies to be carried out.

Large rockets should go in a hanger, where the necessary work is done, with access inside the rocket through special drums. The principal part of the OMBS is a steel cylinder with a diameter of 10 m, made of the emptied rocket tanks which sent them into orbit. It is divided by partitions into additional airtight capsules. All of this increases the strength of this station. For the same purpose, the outer surface of the large cylinder is protected by an aluminum shell attached at a distance of 500 mm from it.

Two tunnels (one for emergency), in which the crew can move, pass along the entire body of the station. The cited nuclear power plant, assembled in the form of a compact pressurized capsule, is withdrawn 18.5 m from the station after the OMBS section is put in orbit and the nose cone is ejected, which decreases the weight and volume of the radiation shield. /69

The booster section is equipped with the equipment and instruments necessary to provide life activity of the crew.

The third principal unit of the station is a telescopically collapsible hanger. It improves the meteorite protection of the rocket itself and the servicing unit. The constant temperature conditions, the uniform illumination (absence of abrupt shadows, which is characteristic of objects on outer space), the feeling of closed space and, consequently, safety, provide for an increase in the productivity of the servicing control. It is suggested that the hanger be pressurized in order to prevent fuel leaks from the rocket tanks, which are dangerous for the control.

It is suggested that the hanger be folded when a spacecraft encounters on OMBS. The nose of the craft enters the reduced hanger and is attached in it. The longitudinal axes of the hanger is unfolded. For a complicated repair, units of the craft should be brought inside the station.

There are two transport drums--a large one for loading and unloading, and a small one for the crew. The large drum has dimensions which permit the cabin of the craft being serviced to go inside the OMBS.

The original idea of launching interplanetary craft from an artificial satellite belongs to K.E. Tsiolkovskiy. The basic idea in favor of this flight pattern was that space rockets could be launched from a satellite-base, developing lower velocities than would be necessary during a launching from the Earth, which means that greater fuel reserves would remain on board for a flight in interplanetary space. Moreover, it was suggested that the rockets could be launched from space stations completely serviced with fuel from the Earth.

Table 3 shows the advantages of interplanetary flights using the OMBS. It gives the necessary takeoff weight with liquid-propellant jet engines (LPRE), (fuel components--liquid hydrogen and oxygen, specific thrust--420 Kg·sec/kg), as calculated for a flight to Mars and return. The weight of all the necessary equipment and reserves is considered in the calculations, for a high degree of regeneration in the life-support system. It was assumed that the oxygen for respiration is regenerated from $CO_2$, while the water comes from the moisture of waste products, and the food is accumulated. The takeoff weight necessary for an analogous flight from an OMBS to the Moon is also presented for the sake of comparison. The takeoff weight necessary for bringing a crew from the Earth onto the OMBS orbit and hook-up with it was not considered. /70

TABLE 3. REQUISITE TAKEOFF WEIGHT OF A CRAFT WITH A LIQUID PROPELLANT JET ENGINE FOR FLIGHTS TO MARS AND THE MOON, m.

| | 1-man crew | | 4-man crew | | 16-man crew | |
|---|---|---|---|---|---|---|
| | Mars | Moon | Mars | Moon | Mars | Moon |
| Flight from OMBS onto orbit around the target and return | 43 | 11 | 160 | 32 | 530 | 111 |
| Flight with landing and return | | | | | | |
| From the Earth | 200 | 46 | 650 | 142 | 2500 | 515 |
| From an OMBS | 67 | 30 | 224 | 90 | 840 | 315 |

As is well known, Soviet scientists developing the idea of K.E. Tsiolkovskiy were the first to realize a launching of a spacecraft from a satellite, a base around the Earth, and to affirm the advantages of this flight pattern experimentally.

First of all, this is important when a rocket puts an automatic interplanetary station on orbit, and the flight of the latter is then corrected only a little. In the case of putting such a /71
station into an orbit which is moving toward a space object directly from the Earth's surface to the point where the last rocket stage is fired, all the errors in navigation accumulated during the preceding stages affect the accuracy of the flight of the AIS toward the target.

In the case of a launching from a space station, all the errors accumulated during the flight of the rocket from the Earth to the satellite orbit can be eliminated.

The more precise parameters of the satellite or launching base in space allow us to "start everything from the beginning" when the engine of the space rocket is fired, and to put the research station into orbit toward a planet, eliminating all the inaccuracies accumulated up to this moment. The second advantage which makes a launching from an orbital station suitable is that, in order to put the craft onto orbit toward any of the planets of the solar system, the engines should impart to it a velocity which is 4-5 times lower than during a takeoff from the Earth. Since the velocities are lower, the errors in velocity are decreased and, consequently, so are the errors in the withdrawal.

One more advantage of a launching from an orbital station is that it provides for derivation of the greatest payload weights. The fact is that, during continuous operation of all the rocket stages, the possible payload weight depends not only on the magnitude of the velocity which must be provided, but also on the angle of inclination toward the horizon. A trajectory inclined sharply toward the horizon can be required toward the end of the acceleration stage in order for a rocket launched from the Earth to take the craft out of the sphere of the Earth's gravitation during continuous acceleration and impart to it the necessary flight direction. The greater this angle, the more strongly the Earth's gravitation prevents acceleration. This results in additional fuel consumption, and high-thrust engines are required for putting a craft of the same weight onto orbit. On the other hand, the satellite is put onto an almost circular orbit, which means minimal fuel consumption and thrust.

The fourth advantage is that a launching from a space base can be carried out at any most convenient point on the trajectory. Specialists find a practically unlimited number of positions from which a rocket can be launched. The moment of launching is not as strictly limited to the position of the ground launching base and the time, as would be the case for a launch from the Earth.

The first advantage of a launch from an OMBS is that it is done more easily when the target or "designated planet" withdraws from the plane of the solar orbit. This allows us to avoid some of the additional special corrections of a rocket for the deviation of the flight target from the plane of the ecliptic during a launch from the Earth. Thus, a launch from an OMBS decreases the possibility of accumulating errors in convergence with the target. /72

We have already mentioned that one of the purposes of a large satellite base is to provide spacecraft with a preliminary fuel supply. But where on the base does the fuel which should be supplied, for example, to lunar and interplanetary craft come from? The fuel can be supplied by cargo rockets from the Earth. Actually, this can be done but is is extremely expensive.

There is one more method--extract some of the fuel directly... on orbit. The very traces of the air envelope of a planet which decelerate the craft can be accumulated and used. This plan has been affirmed by a careful computational analysis.[9] The plan includes the design of an artificial satellite moving along an orbit of the Earth at an altitude of about 100 km, or along an orbit around a planet in the atmospheres of other planets, collecting and accumulating the air. The aerodynamic forms of the air intake, the design ff the pump feeding the air which is captured during the flight, and the methods of liquifying this air have been investigated. Engines which permit maintaining the artificial satellite on orbit and controlling it have also been investigated.

Figure 8 will help acquaint us with the design of the apparatus of such an artificial Earth satellite. The air, whose density is roughly a million times less at an altitude of 100 km than on the Earth, enters the air intake 1, with diameter up to 30 m, and then goes to the cooling system with the pump 6. Being cooled in a number of heat exchangers, where helium is used as the cooling liquid, the air is liquified. The liquid air is pumped to the tank 9.

The power demands of the artificial satellite are provided by the energy discharged during the nuclear process in the reactor 2. The boiling of an alkali metal in the steam generator provides

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[9] Demetriades, S.T.: Preliminary Study of Propulsive Fluid Accumulator Systems. "Journal of the British Interplanetary Society", Vol. 18, No. 10, 1962.

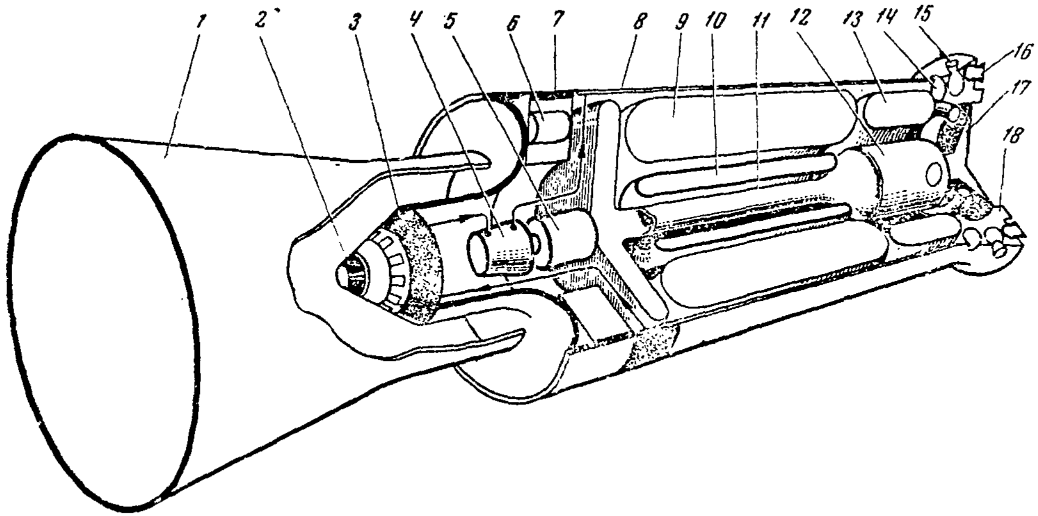


Fig. 8. Design of Orbital Aircraft.
(1) Air Intake; (2) Nuclear Reactor and Steam Generator; (3) Shield; (4) Drum; (5) Electric Generator; (6) Helium Pump; (7) Pump Radiator; (8) Emitter of Turbogenerator; (9) Tank with Liquid Air; (10) Tank with Liquid Oxygen; (11) Tunnel for Crew; (12) Section for Crew; (13) Tank with Liquid Hydrogen; (14, 15) Electric Rocket Engines; (16) Chemical Auxiliary Rocket Engine; (17) Hook-up Surface for Linking During Encounter; (18) Auxiliary Device for Realizing an Encounter.

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the thermal energy. The steam goes to the turbine 4, which rotates the electric generator 5. The spent steam goes to the condensor 8, which is situated on the surface of the artificial satellite, and again returns to the steam generator. The electric rocket engines 14 and 15 guarantee that the apparatus will remain in orbit. In one of them, some of the air trapped through the air intake is picked up and ejected with increased velocity. The chemical auxiliary rocket engines 16 and the hook-up surface 17, which is intended for connection with spacecraft, permit the necessary maneuvers when the spacecraft comes to the area 17 for maintenance. /74

The artificial satellite is serviced by a crew in the cabin 12. The members of the servicing crew have access to the most important units of the artificial satellite along inside corridors. The shield 3 and the turbogenerator protect the crew from the emissions of the reactor. The oxygen in tank 11 provides respiration for the crew and, if necessary, guarantees operation of auxiliary engines, together with the hydrogen in the annular tank 13.

At an altitude of 100 km, roughly 1.5 kg of air enters the accumulator in one day per $m^2$ of the air intake. Consequently, the air intake with diameter of 30 m collects about 700 kg of air in one day, and 265 tons in one year! Unfortunately, all this air cannot be accumulated: a thrust must be produced, which means that the working fluid must be consumed, in order to maintain this device which accumulates the air. Some of the air accumulated can serve as this working fluid. It is obvious that, during movement along an orbit at a speed of 8 km/sec, in using half of the trapped air for producing the thrust, it should be ejected at a velocity greater than 16 km/sec. An electric rocket engine operating on the energy of an atomic reactor can do this successfully. When the mass of the air used for producing the thrust is decreased, its exhaust velocity should be increased; however, the possibilities in this direction are limited.

The fact that a nuclear engine should have at least 1000 times greater power for boosting some load into orbit around the Earth than that required for an artificial satellite to accumulate the same amount of air on orbit in 25 days is an example of the great advantages of an air-accumulator-satellite.

The launching of a load of 20 tons from the Earth to the Moon /75 can be done with the aid of an artificial satellite weighing 26 tons which is put on a 100-kilometer orbit. In order to convey a load of 9 tons on the Moon, with a soft landing on its surface and subsequent return, there must be an accumulator-satellite weighing about 70 tons (let us remember that the in-flight weight of the TU-104 is 73 tons) and a spacecraft weighing about 40 tons with payload of 16 tons. Moreover, it would be necessary to accumulate 180 tons of air on orbit for such a flight. In this case, a 70-ton accumulator would aid in supply fuel 3 times a year. An accumulator-satellite is particularly convenient when it is used as a base servicing regular flights in space. The advantages of the plant described become particularly obvious when constructing a second accumulator-satellite on orbit near the planet-target. This is easily understood by examining Figure 9; the number of circular flights *n* of an apparatus with payload of 32 tons, from an orbit around the Earth to the Mars orbit and back in 170 days, is plotted along the horizontal axis. The mass *M* (per 1000 tons) necessary for these flights on orbit near the Earth is plotted along the vertical axis.

An artificial satellite with an accumulator can decrease the cost of research studies on space to a great extent, and can become a reliable reference base there.

We have enumerated only some of the potentials of "specialized" artificial satellites. Multi-purpose satellites could also be designed. Let us list some such purposes: laboratories for determining the characteristics of the upper atmosphere, the space around the Earth, for finding the geometric dimensions of the Earth, the distances between mainlands and other geophysical changes, the structure of the Earth and its magnetic fields, magnetic anomalies and their depth, the distribution of cosmic rays; a study of the particular characteristics of the radiowaves propagation in the upper atmosphere, and the danger of meteorites; an investigation of biological phenomena under the conditions of weightlessness.

It is indisputable that the construction and protection of artificial satellites is the basic method of mastering the space surrounding the Earth, which will aid in making further steps into outer space. /76

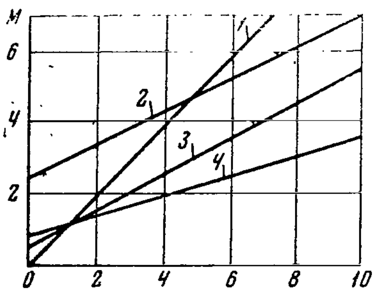


Fig. 9. Dependence of the Mass of a Power Plant on Orbit Around the Earth m on the Number of Flights to Mars n With and Without an OMBS System. (1) Nuclear Power Plant (Working Fluid, Hydrogen); (2) One OMBS System on Orbit Around the Earth; (3) One OMBS System on Orbit Around Mars; (4) Two OMBS Systems on Orbits--One Around Earth, the Other Around Mars.

The natural satellite, the Moon, will also become in time an artificial satellite, in the sense that equipment and groups of scientists will be landed on it. This began on February 3, 1966 when the Soviet automatic station "Luna-9" made a soft landing on the Moon in the region of Oceanus Procellarum.

Years will pass, and satellites over the planet will become part of the life of the Earth inhabitants, just as we have become accustomed to television, transistors, and jets.

## Power Plants in Spacecraft

First of all, let us examine the operational principles and some particular characteristics of certain different engine designs for spacecraft, in order to select those which can be used for future voyages in space. These engines can be divided, for example, according to the method of transferring the heat, the working fluid ejected from the rocket, into three groups: (1) engines for which the mixture formed in the chamber serves simultaneously as the source of heat and the working fluid (w.f.). During the outflow of the working fluid (substance) from the nozzle, the rocket thrust is produced.

(2) engines for which the source of heat and the working fluid are separated. With this design, the working fluid is heated, passing, for example, through an atomic reactor;

(3) engines for which there are devices which transmit energy to the working fluid between the source of heat and the working fluid.

The weight ratio of the power plant in the spacecraft is characterized by its specific weight $\gamma_{en}$ i.e., by the ratio between the /77 total weight of the power plant (the weight of the apparatus minus the payload and the fuel weight) and the total engine thrust. Let us assume that this ratio remains unchanged as the initial weight of the power plant decreases (for example, during the ejection of emptied tanks or stages), and the thrust decreases correspondingly:

$$\frac{G_{en}}{P_p} = \gamma_{en}, \text{ Kg/Kg}. \tag{2.1}$$

In particular, the specific weight characterizes the allowable acceleration, or the rate of acceleration of the aircraft, and consequently, it also determines the time for traveling a certain distance.

In evaluating the engines, we must also turn to another important parameter--the so-called specific thrust $P_{sp}$, i.e., the thrust which can be obtained if 1 kg of fuel is consumed in the engine in 1 second. In order to calculate the specific thrust (specific impulse), we must divide the total engine thrust (in kg) by the total fuel consumption per second (kg):

$$\frac{P_p}{G_f} = P_{sp}, \text{ Kg·sec/Kg}. \tag{2.2}$$

The specific thrust determines the specific consumption of fuel $G_{f.sp.}$ necessary for producing 1 kg thrust, e.g., per sec:

$$\frac{G_f}{P_p} = G_{f.sp.}, \text{ Kg/Kg·sec.}$$

If the engine thrust is determined in the modern International System of Units, then its value in newtons is 9.8. times greater, while the scale and magnitude of the specific thrust coincide with the escape velocity (approximately).

In determining the specific engine thrust, we must also consider the fuel consumption necessary for actuating different auxiliary devices, e.g., devices which supply the working fluid, feed the automatic apparatus, and for the ion engine, the evaporator.

The greater the specific thrust, the less the specific fuel consumption, i.e., the better the economy of the engine. An in- /78
crease in the specific thrust can decrease the ratio between the initial takeoff weight of the apparatus and its final weight.

The value for the specific thrust of a rocket engine depends on the thermal efficiency $\eta_t$, i.e., the ratio between the kinetic energy which is imparted to the working fluid and the efficiency of the fuel:

$$\eta_t = \frac{v^2_{w.f.}}{2gAH_u}, \qquad (2.3)$$

where $v_{w.f.}$ is the escape velocity of the working fluid in m/sec; $g$ is the acceleration of gravity, m/sec$^2$; $H_u$ is the fuel efficiency, Kcal/kg; $A$ = 427 is the mechanical heat equivalent, kgm/Kcal.

The conversion of the efficiency of the fuel into the kinetic energy of the stream occurs with losses; some of the heat is carried off with the escaping fluid, and some is not released (incompleteness of combustion).

The specific thrust can be calculated by dividing the exhaust velocity by 9.81.

The exhaust velocity is found from (2.3):

$$v_{w.f.} = \sqrt{2gAH_u\eta_t} = 91.5\sqrt{H_u\eta_t}. \qquad (2.4)$$

Consequently, the exhaust velocity and specific thrust increase when the fuel efficiency and thermal efficiency increase. An increase of the fuel efficiency due, for example, through the use of the nuclear fuel $U^{235}$ is one of the most effective methods of increasing the specific thrust.

Using a fuel of higher efficiency, we can obtain such temperatures that thermal insulation of the walls of the combustion chamber from overheating becomes structurally unfeasible. We must turn to other engine designs which do not require such high heating. The specific thrusts which can be obtained by using engines will be represented later in Figure 36.

We will now attempt to describe the prospects of using different engines for spacecraft.

### Prospects of "Chemical" Rockets

/79

The rocket is a moving body with mass which increases during the operation of its engine.

More than half a century ago, K.E. Tsiolkovskiy said that the final characteristic velocity of the rocket, i.e., its velocity when there is no effect of any external forces, can be determined from the following equation:

$$v_k = v_{w.f.} \ln \frac{M_0}{M_k} = 9.81 P_{sp.} \ln z, \tag{2.5}$$

where $v_{w.f.}$ is the exhaust velocity of the gases (working fluid) from the combustion chamber; $M_0$ is the initial mass of the rocket (in launching); $M_k$ is the final mass of the rocket.

It follows from Tsiolkovskiy's formula that, if a rocket is 63% filled with fuel, i.e., when its initial mass is 2.7 times greater than the final one, the flight speed of the rocket reaches only the exhaust velocity of the gases from its nozzle (since ln 2.7 = 1). For a further increase in the flight speed, we must lighten its structure while increasing the amount of fuel on board.

However, the prospects of increasing the mass ratio are limited. Actually, an ordinary water bucket weighs roughly 1 kg and holds about 14 kg of liquid and, thus, the mass ratio for it is only 15; railroad tank cars hold roughly 13 times more fuel than they themselves weigh. Such a mass ratio cannot be attained for a single-stage rocket. In addition to the fuel and the place to put it, a large amount of the weight of the rocket should be attributed to its envelope, which is fastened by special elements, numerous apparatus which guarantee the preservation and supply of fuel to the combustion chambers of high-power engines, the automatic control devices, etc.

The reader has certainly heard of the single-stage ballistic rocket A-4, which was used after the war for studying the upper layers of the atmosphere (Fig. 10). Its length is about 14 m, the takeoff weight is roughly 13 tons, the greatest diameter is 165 cm. Research instruments were put in the cone-shaped forepart of the rocket. The equipment for automatic control of the rocket and the tank, containing about 3 tons of fuel (hydrocarbon-alcohol) were then installed. Then followed the tank with oxidizer, which held about 5 tons of liquid oxygen. /80

A speical device supplied the fuel and oxidizers to the combustion chamber, from which the gases escaped through the nozzle, a channel which first contracted up to the section in which the gas velocity reached the speed of sound and then expanded like a horn, which guaranteeded gas exhaust at a supersonic speed.

The aerodynamic and jet vanes fixed in the flow of gas escaping from the nozzle served as the outer organs for stabilization and control of the rocket flight. The rockets were controlled in "airless" space with the aid of jet vanes.

A power of about 465 hp was developed in a few seconds after starting up the turbine which rotated the centrifugal pumps of the rocket. Generating a pressure up to 50 atm, the pump guaranteed a supply of 125 kg fuel/sec. The engine thrust increased up to 25 tons, and the rockets took off vertically, reaching an altitude of 180 km above ground level.

Since the production of the first large-scale ballistic apparatus, they have been developed extremely rapidly. The designs of the hulls and rocket engines have been continuously improved. For the rocket we have just described, the structural weight was roughly 1/3 the total weight, but it is much less for modern rockets. A schematic diagram of one of the modern rockets[10] is shown in Figure 11, at the center of which we can find the first stage with 8 combustion chambers each of which should provide a thrust of 85 tons.

The capacity of the high-power apparatus of large scale modern rockets, which produce several hundreds of tons, reaches several millions of hp at the highest flight speed of the first stages, although in a short period. A hydroelectric power station of such capacity would surpass the Kuybyshev hydroelectric power plant in scale. The buildings of the Kuybyshev power plant occupy a territory in which the most powerful modern rocket, several tens of meters long, would appear to be only a small peg; actually, the Soviet space rocket which guaranteed the flight of the first astronauts in the world developed a thrust of about 600 tons and power of 20 million hp, i.e., 8 times more than the power of the Kuybyshev hydroelectric plant.

[10] "Saturn-1", U.S.A.

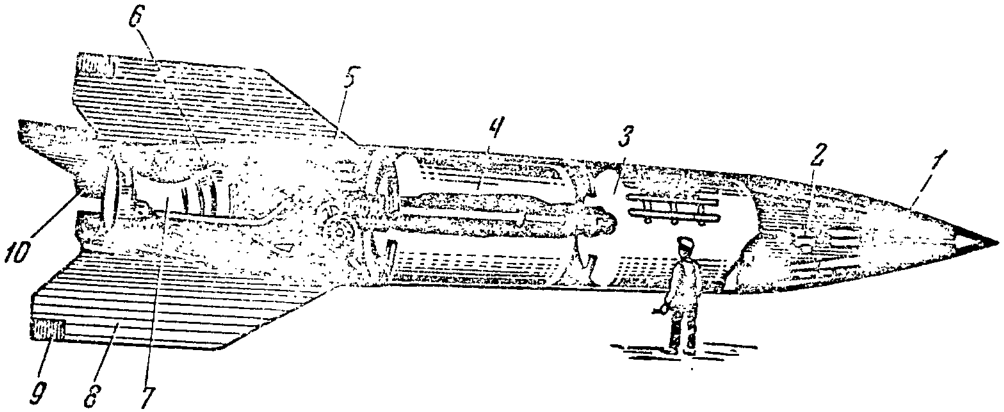


Fig. 10. Schematic Diagram of One of the First Ballistic Rockets Used for Studying the Upper Layers of the Atmosphere. (1) Payload; (2) Instruments and Automata for Control; (3) Tank with Fuel; (4) Tank with Oxidizer; (5) Turbopump Assembly (TPA); (6) Combustion Chamber; (7) Nozzle; (8) Air Stabilizers; (9) Air Vanes; (10) Jet Vanes.

/81

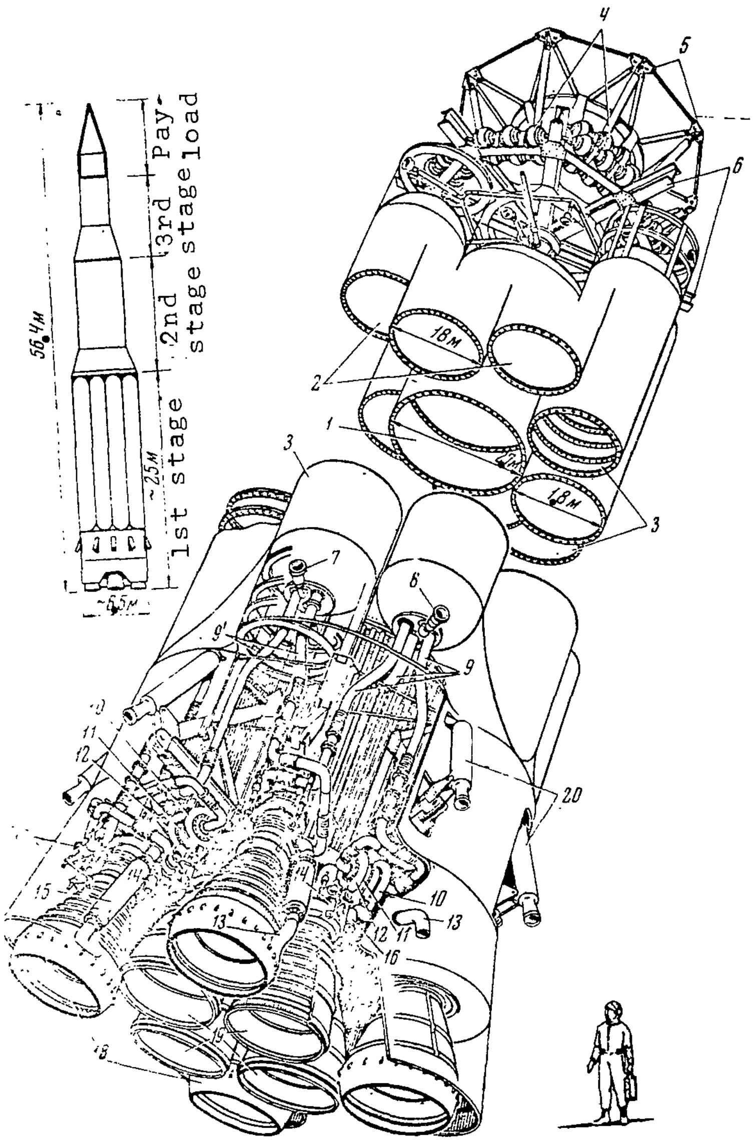


Fig. 11. One of the Prospective Rocket Apparatus
Top Left-General Appearance of the Rocket:
In the Middle-Component Scheme of the First Launching Rocket Stage with 8 Engines, 85 Tons Thrust Each. (1) Central Tank with Oxidizer-Liquid Oxygen; (2) Outer Tanks with Oxidizer-Liquid Oxygen; (3) Tanks for Fuel - Kerosene; (4) Liquid Inertial Helium Gas Tanks for Expelling the Fuel Components from the Fuel Tanks; (5) Points of Attachment of the Second Stage; (6) Lower Part of the Frame Connecting the Structures of the First and Second Stages; (7) Fueling Neck; (8) Filler Neck for Oxidizer; (9) and (9') Turbo-pump Oxidizer and Fuel Feed Systems; (10) Oxidizer Pump; (11) Turbine of Turbopump Assembly (TPA); (12) Fuel Pump; (13) TPA Exhaust; (14) Powder (Cartridge) Gas Generator for Triggering the TPA; (15) Heat Exchanger; (16) Tank with TPA Lubricants; (17) Hydraulic Drives of Rotating Combustion Chambers; (18) External Combustion Chambers (Rotating); (19) Internal Fixed Combustion Chambers; (20) Retrorocket Engines of Re-entry System.

/82

In order to increase the amount of reserved fuel compared to the final mass of the rocket structure and payload, it should be made in the form of a composit "melting" train, i.e., a rocket of several stages. In this case, after using the fuel for the first stage, it is ejected, and the engine of the following stage begins to operate, etc. /83

The characteristic velocity of a multi-stage rocket, i.e., the maximum velocity achieved in a flight in vacuum and without a consideration of the gravitation, is equal to the sum of the products of the exhaust velocities, multiplied by the hyperbolic logarithms of the ratios between the initial and final masses for each stage. If the exhaust velocities and mass ratios $M \frac{M_0}{M_K}$ are identical for each of the stages, then, in order to reach the highest characteristic velocity of the last stage (load) of the rockets, the initial masses of the stages should be distributed according to the rule of geometric progression. The characteristic velocity of such a rocket of $n$ stages is expressed by the following dependent:

$$v_K = nv_{w.f.} \ln \frac{1}{\frac{1}{M} + \left(\frac{M_p}{M_0}\right)^{\frac{1}{n}}} \quad (2.6)$$

where $M_p$ is the payload mass; $M$ is the constant mass ratio for each stage; n is the number of stages; $v_{w.f.}$ is the exhaust velocity of the working fluid. /84

The optimal number of stages guaranteeing the minimal ratio $\frac{M_0}{M_p}$ occurs in dependence on the ratio $\frac{V_k}{V_{w.f.}}$.

It was in this multi-stage variation that we succeeded in designing the Soviet intercontinental ballistic rocket with flight speed of 25,000 km/hr, then in boosting satellites up to velocities of 30,000 km/hr, and, finally, in launching a space rocket with velocity of about 40,000 km/hr. However, when the number of stages increases, the rocket becomes more and more structurally, complicated and the velocity gain decreases.

The velocities attained for the exhaust gases from the chambers of thermochemical rockets are roughly 2 km/sec for solid fuels, and more than 3 km/sec for modern liquid fuels.

As calculations show, the highest permissible exhaust velocity when chemical fuels are used is about 5.5 km/sec. Thus, in view of the relatively low maximal flight speeds, rockets operating on a chemical fuel are unsuitable for flight beyond the boundaries of the solar system. The dependences in Figure 12 show this, where the ratios between the initial mass of a multi-stage rocket and the mass of its payload for an optimal number of stages are represented as a function of the characteristic velocity, computed according to the equation $v_k = kv_{w.f.} \ln \frac{M_0}{M_p}$ for the case when the rocket structure is quite perfected: $\overline{M} = 10$, $k = 0.67$. Even now, liquid propellant rocket engines can guarantee flights in the space around the Sun up to an orbit around Jupiter. As for flights to Pluto with re-entry, a modern rocket with LPRE would need about 100 years for such a voyage, which is not appealing.

A space rocket with LPRE is essentially similar to a ballistic rocket. Actually, after completing the controlled flight, by the effect of the force of gravity in a relatively small active segment of the trajectory, it flies the remaining, greater part of the trajectory with the engine turned off. Thus, the flight of a space rocket is similar to the "delayed firing" of a projectile flown out of a gun with very long barrel, along which it moves for 100-300 seconds, and then flies in space for months or even years. The automatic stations "Mars-1", "Mariner-2", "Venera-2" and "Venera-3" flew in this way to the close planets of the solar system. Whether or not the target is reached depends mainly on the accuracy of the ballistic calculations. The rocket is controlled only slightly during most of the rocket trajectory. When the distance increases, the difficulty of hitting the target increases. This is also one of the reasons why the liquid-propellant rocket engine, which is an ideal engine for firing some mass from the Earth and transporting it onto orbit around the Earth, is far from the best for long-range flights into outer space. It should make way for long-range engines which operate a great deal of the way. /85

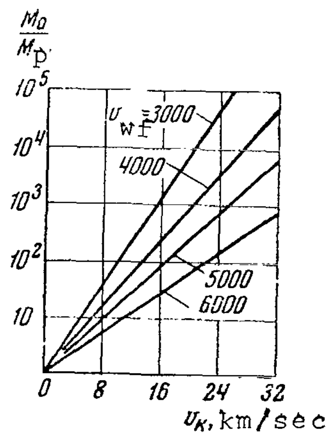


Fig. 12. Ratio Between Initial Rocket Weight and Weight of its Payload $\frac{M_0}{M_p}$ as a Function of the Characteristic Velocity $v_k$ at $\overline{M} = \frac{M_0}{M_k} = 10$ (for Each Stage), $k = 0.67$.

## Nuclear Engines

In 1921, Tsiolkovskiy wrote: "The splitting of atoms is a vast source of energy"[11]. Today, when specialists are studying nuclear

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[11] Tsiolkovskiy, K.E.: Issledovaniye mirovykk prostranstv reaktivnymi priborami (Studying Outer Space with Jet-Propelled Apparatus). Collected Works, Vol. II, Moscow, Akad, Nauk S.S.S.R., 1959.

engines for spacecraft in detail, this is an example of a significant scientific prediction.

Let us discuss some of the numerous designs of nuclear rocket engines.[12] Three basic designs are possible: with gradual heat three basic designs are possible: with gradual heat transfer to the working fluid, with the ejection of part of the nuclear fuel and finally, with the use of a nuclear bomb. /86

Let us examine the first of the proposed designs, which is similar to the regular LPRE, but such that there is no oxidizer in it, and a special working fluid is used instead of fuel, while a reactor replaces the combustion chamber (Figure 13). Thus, the energy source and the working fuel are separate. The working fluid is pumped through the active hot zone of the reactor. In this, it is evaporated, heated, and expanded, it flows through the nozzle, producing thrust. This thermal atomic rocket engine is feasible.

What are its advantages compared to the liquid-propellant rocket engine, and why can they be obtained by using an atomic rocket engine?

We mentioned above that the exhaust velocity of a working fluid from a rocket nozzle increases, which means that the specific thrust increases, when the fuel efficiency increases. As calculations show, when using chemical fuels, the highest possible exhaust velocity is about 5.5 km/sec.

When using the nuclear propellant $U^{235}$, the efficiency of which is roughly 2 million times greater than that of an chemical propellants, the amount of profitable heat would increase roughly by a factor of 1400, compared to a chemical fuel. However, an increase in the efficiency of a fuel during its direct usage in a combustion chamber is possible only as long as we can cope with the problem of protecting its walls from overheating.

Another advantage of the atomic rocket engine is that, when using it, it is no longer necessary to be concerned about oxidation of the fuel and, therefore, new prospects are opendd for selecting the propelling agents. For such an agent, we could use only one fluid with relatively low molecular weight and rather high density. It is advantageous to decrease the molecular weight since, for example, in decreasing the molecular weight by a factor of 2.25, the exhaust velocity increases by a factor of 1.5. On the other hand, an increase of the fuel density aids in decreasing the dimensions and, consequently the weight of the rockets tanks.

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[12] See Perel'man, R.G.: Yadernyye dvigateli (Nuclear Engines). "Znaniye", 1958.

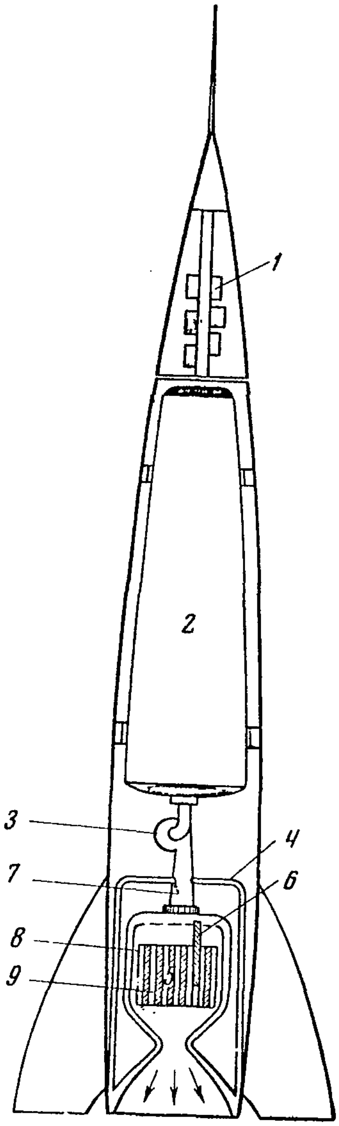


Fig. 13. Schematic Diagram of Atomic Rockets With Reactor Installed in the Chamber. (1) Instruments and Automata for Control of the Rocket; (2) Tank for Liquid Hydrogen; (3) Turbopump Assembly; (4) Outlet of Some of the Hydrogen for Cooling the Engine "Chamber"; (5) Reactor; (6) Controlling Rod; (7) Liquid Hydrogen Feed Pump; (8) Graphite Blocks; (9) Rods Containing Nuclear Propellant. /87

If we could fulfill all these possibilities, we could count on new colossal advances in rocket technology. However, in the "simplest" variation of the atomic rocket engine in which a uranium-graphite reactor is used for heating the working fluid, it is extremely difficult to take full advantage of the nuclear propellent, primarily its high efficiency.

In the variation where liquid hydrogen is heated in the reactor, the efficiency of the nuclear fuel is used to a slight degree. The advantages are due only to the use of a work fluid /88 with low molecular weight, and the exhaust velocity increases by a factor of 3-4,[13] compared to the permissible velocity of an LPRE using the most effective chemical fuel. The reason is that the working fluid must be heated by the heat emission from the reactor. This means that its material should be heated up to even higher temperatures, which are limited by the heat resistance of the material (graphite). The need for transmitting huge amounts of heat and intensifying the heat emission requires that the surfaces be developed to a maximum degree, the pressures be increased and the temperatures of the working fluid be decreased, so that a high temperature differential is guaranteed.

In the design proposed by Tsan Chen-Soo, it was suggested that a reactor consisting of conical uranium-carbon tubes with porous walls, each roughly 3 mm thick, be used. The liquid hydrogen should be pumped through the porous walls of the tubes, which provides for a large area of heat exchange, cools them and is itself heated. The suggested initial weight of the rocket with the honeycomb type reactor is about 1600 tons for flight to the Moon, and there should be 1200 tons of liquid hydrogen in it, in the rocket tanks.

Can we really reject a reactor filled with a solid moderator and nuclear propellent, which limits the temperature, and nevertheless achieve a high heating of the working fluid? This is essentially possible if we can apply the engine design which can be conditionally called the design with ejection of some of the nuclear propellent. Let us discuss two variations of this design.[14]

An engine of the liquid-propellant type with an active plasma zone and a "fluidized bed" was suggested. Here, enriched gaseous nuclear fuel and a liquid working fluid are sent directly to a

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[13] See: Journal of the Royal Aeronautical Society, Vol. 5, 1963.

[14] See: S.L. Kerrebrok and R.V. Meghreblian: Aero Space Sci., No. 9, 1961; R.V. Meghreblian: Astronautics, No. VII, 1961; No. XII, 1962.

chamber with walls which reflect neutrons well and have special cooling properties. For example, if a working fluid which serves simultaneously as the moderator is pressed inside through tangential apertures in the walls, and a gaseous nuclear propellant is fed into the chamber at the same time, then a chain reaction begins when the critical mass is reached. At the center of the chamber in the active zone, the temperature can be extremely high, while its walls, from which heat is continuously derived by the working fluid which passes through them and then evaporates, remain cold and can hold out. It is assumed that an engine of this design will yield specific impulse of $10^3$ kg·sec/kg. /89

Another modification of this design (Figure 14) with a gaseous working fluid feed is also being investigated. In this design, a gaseous working fluid and a nuclear propellant are injected tangentially in order to produce a spiral vortex filament along the walls. This aids in limiting the high-temperature zone, protecting the walls from neutron bombardment and thus increasing their strength.

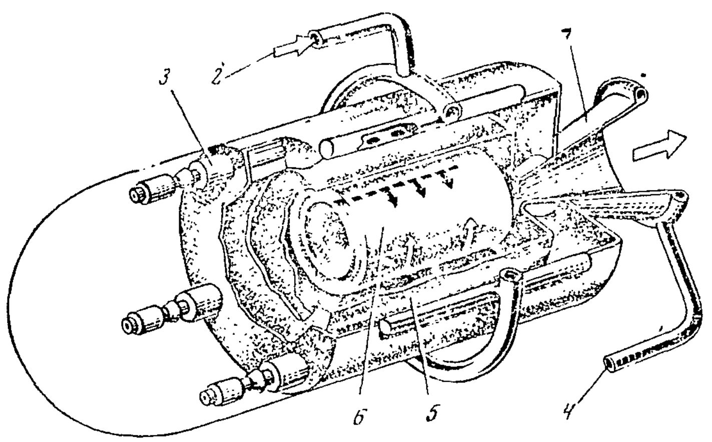


Fig. 14. Schematic Diagram of Engine with Gaseous Active Zone and Vortex Filament of the Nuclear Propellant. (1) Nozzle Cooled by Liquid Working Fluid; (2) Tangential Feed of Nuclear Propellants; (3) Regulating Organs in the Form of Rotating Drums; (4) Feed of Working Fluid, Cooling the Nozzle and Walls of the Chamber; (5) Reflector; (6) Vortex.

Because the molecules of the nuclear propellant have great mass, greater forces are required to deflect their trajectory; as a result, the vortex filaments "isolate" the nuclear propellant on its outer surface. At the same time, it is pushed off the wall by a continuous gas flow. Because of the simultaneous action of aerodynamic and centrifugal forces, the Vortex filament does not touch the walls and it keeps most of the nuclear propellants on its surface, "isolating" the heated working fluid flowing through the nozzle from the inner surface. /90

The realization of an engine of the design described is complicated in that, in order to produce the critical mass of the gaseous nuclear propellant and to obtain the chain reaction in a chamber of suitable dimensions, very high pressures (hundreds and even thousands of atm) must be produced, so that the density might increase. Reliable cooled reflectors should be used, and they must not "allow" the neutrons providing for the chain process out of the chamber. We must have systems which keep the greatest possible amount of nuclear propellant inside the engine. In addition to the centrifugal separation, one of the methods proposed for this purpose is the suggested use of ionization of uranium atoms at high temperatures in order to keep them on the periphery of the chamber with the aid of powerful electromagnetic fields. However, the weight of the electrical equipment necessary to produce them can be extreme.

Another idea suggested for the design of a nuclear rocket with ejection of the mass containing the disintegration produces is the use of a rod of a solid nuclear propellant enclosed in an envelope made of a neutron absorbent, for example, cadmium. It is suggested that a chain reaction should occur as part of the envelope is gradually removed. It would then be very tempting to use the fragments of the nuclei formed during this reaction in order to eject them with the ordered jet from the nozzle. The velocity of these particles at the moment of fission is tens of thousands of kilometers per second, while the amount of fissionable material can be computed in kilograms. However, this attractive design is immediately confronted with extreme difficulties. The fact is that, during the disintegration of only 1 g of uranium $U^{235}$, the amount of heat released corresponds to a power of 100 million hp. The heat capacity of the nuclear rocket engine reaches billions /91
of hp, which is comparable to an atomic explosion in a combustion chamber. This would bring about instantaneous evaporation of the chamber. That is why the need for ballasting the processes in the chamber is stipulated in numerous publications.[15] It is suggested that, for this purpose, a uranium rod should be enclosed in a fixed envelope of the working fluid (for example, lithium hydride). The nuclear reaction evaporates the working fluid and the incandescent gases, in which only 100 weight percentage of the nuclear propellant is contained, produced the thrust after flowing out of the nozzle.

However, methods which would retard the rate of propagation of the reaction over the rod have still not been found. In the case of ballasting with the working fluid also, an explosion which is "too rapid" would probably bring about the destruction of the chamber. So that the engine we have described might become feasible, there must be a deceleration of the rate of propagation of the reaction.

A pulsejet engine is suggested for high-power rockets; in its chamber, there is an atomic explosion equivalent in power roughly to a 10-ton TNT bomb, enclosed in a capsule filled with water each second. The heat released evaporates and decomposes the water and the vapor flowing out produces the thrust.

Since the possibility of designing a chamber which can sustain the explosion of a bomb is doubtful, in most of the designs suggested for a "explosive" engine, the bomb is transported outside the chamber and then explodes some distance from the apparatus, which is equipped with a special deflector encompassing as much of the space behind the apparatus as possible.

In the explosion of a bomb, there is first an emission of radiant energy. As a result of this partial absorption, a layer of the material applied on the field evaporates. This imparts to the apparatus a pulse in the direction of the flight. Then the particles, or the explosion products, reach the screen, and transfer their momentum to it. A series of bombs exploding one after another could be like briefly-acting rocket stages, boosting the apparatus.

The difficulties of shielding the apparatus and crew from the /92
abrupt impulses caused by the explosions, the focusing of the energy of the explosion in order to decrease the losses in nuclear propellants, the problem of maintaining steady motion of the apparatus, are only some of the problems standing in the way of the design of such an engine. Finally, the international ban on nuclear armament tests in three spheres denies a ground or atmospheric testing of rockets with engines operating on the ejection of a nuclear propellant, particularly an atomic explosion. All this makes the design of such an engine very problematic. At the same time, an engine using the heat transfer in an atomic reactor can be developed successful under ground conditions.

Finally, let us discuss the hypothetical plans for a thermonuclear engine, which will become possible only when a thermonuclear reactor with a self-sustaining stable reaction is developed. Let us remember that, in this case, energy would be released due to a decrease of roughly 1/100 the rest mass of the substance taking part in the reaction.

The plasma in the active zone of the thermonuclear reactor will have a temperature higher than $10^8$ . If some of this substance could be directed toward the nozzle and there could be a "controlled plasma leakage", then extremely high specific thrusts could be obtained ($5 \cdot 10^5 - 3 \cdot 10^6$ kg·sec/kg). Naturally, a small amount of the substance should be constantly fed in to compensate for the leakage into the reaction zone.

One of the principal designs of a thermonuclear engine with a thermonuclear reaction zone surrounded by double walls, between which the working fluid (e.g., lithium) flows, is shown in Figure 15. Some of it is injected through the aperture into the reaction zone. Moving along the walls, the lithium is heated and ejected through the nozzle in order to produce the thrust. Another amount of the lithium is evaporated in the space between the walls. The vapor is fed into the turbogenerator, which develops the electric energy for the magnetic mirrors and all the auxilliary systems.

The reaction $D + H^3 \rightarrow H^4 + H$ (60% $He^3$, 40% D) is most suitable for application in outer space. Since a neutron emission, which requires particularly heavy shields for protection, is yielded in this case only by the side reactions, the energy of the neutron emission is only 1.5% the total amount of energy released. /93

An aircraft with this hypothetical thermonuclear reactor was examined in one of the recently published foreign computing studies.[16] It is suggested that plasma confinement should be carried out by an external magnetic field in the form of a combined multipolar system. It is suggested that conductors made of intermetallic niobium and tin compounds[17], which have superconducting properties guaranteeing current densities of about $15.10^4$ a/cm$^2$, should be used in order to obtain confined magnetic fields of the requisite intensity higher than $2.10^5$ gauss. The construction, attachment and cooling of a system of such superconducting coils is one of the principal problems in designing the engine.

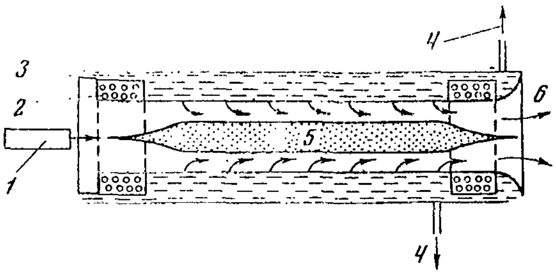


Fig. 15. Hypothetical Thermonuclear Engine. (1) Ion Gun; (2) Coils of Magnetic Mirrors; (3) Liquid Lithium Feed; (4) Lithium Vapor Feed to Power Plant Developing Electric Energy; (5) Thermonuclear Reaction Zone; (6) Discharge.

The structural design of the magnetic thrust chamber of the thermonuclear engine consists of a complex system of coils of a

[16] Hilton, J.L., J.S. Luce, A.S. Thomson. Journal of Spacecraft and Rockets, No. 3, p. 276-282, 1964.

[17] See: Kunzler, J.E., E. Buchler, F.S. Hsu and J.H. Wernick. Phys. Rev. Letters, Vol. 6, 89, 1961.

longitudinal, lateral and a number of auxiliary fields. A very large amount of heat released in the material of the structure during absorption of the nuclear emission must be led off this "magnetic bottle". The coils should be cooled with gaseous helium, /94 in order to preserve their superconductivity. However, the discharge of heat into outer space by a coolant-radiator is almost impossible in this case. A great deal of power must be consumed in order to feed the special cooling devices.

In order to increase the absolute value of the thrust roughly up to 0.5 kg with a corresponding decrease in the specific impulse by a factor of 100, the working fluid ($D_2H_2$) can be mixed with the "fuel" at the output. A multi-layered lithium hydride shield protects the crew and machinery.

A reliable estimate of the weight of the thermonuclear engines is still impossible. Obviously, they will hold a middle position between thermal and electric rocket engines. In the most scientifically-founded thermonuclear engine design described above, the ratio between the total weight and the reaction yield is 1.8 kg/KW. At the same time, the controllable high-energy thermonuclear reactor can become an unsurpassed source of energy for electric rocket engines and, thus, their component parts.

The tests carried out in the U.S.A. with prototypes of such engines, which were equipped with uranium-graphite reactors, are one example of the development of nuclear engines with heat exchange to the working fluid in the reactor. After a number of failures, hot tests of the reactor Kiwi B4-D (Figure 16) were carried out in May 1964. The reactor worked normally for 30 seconds, developing a thrust of about 23 tons with $P_{sp} \sim$ 700 Kg·sec/kg.

We must overcome the erosion of the heat-releasing elements by the working fluid, which is accompanied by the ejection of radio active products, and we must learn how to trigger the reactor reliably and control it. The difficulties are great, and many specialists consider that a nuclear engine of such a type will not be put on rockets until 1970. However, the promising prospects of nuclear engines apparatus is indisputable, and this is inducing many researchers to work exhaustingly over its design.

It is most expedient uo use a nuclear engine for space flights in the middle state of a rocket operating in outer space.

It is also possible to assemble a nuclear stage on an orbit, to which its parts are sent from the Earth by rockets operating on liquid propellant. In the case of a direct launching from the Earth, in one of the variations the first and booster stage can have a high-power solid- or liquid-propellant engine. After it accelerates the rocket up to a velocity of 1.5 - 2 thousand km/hr, the stage with ramjet engine goes into action and accelerates the

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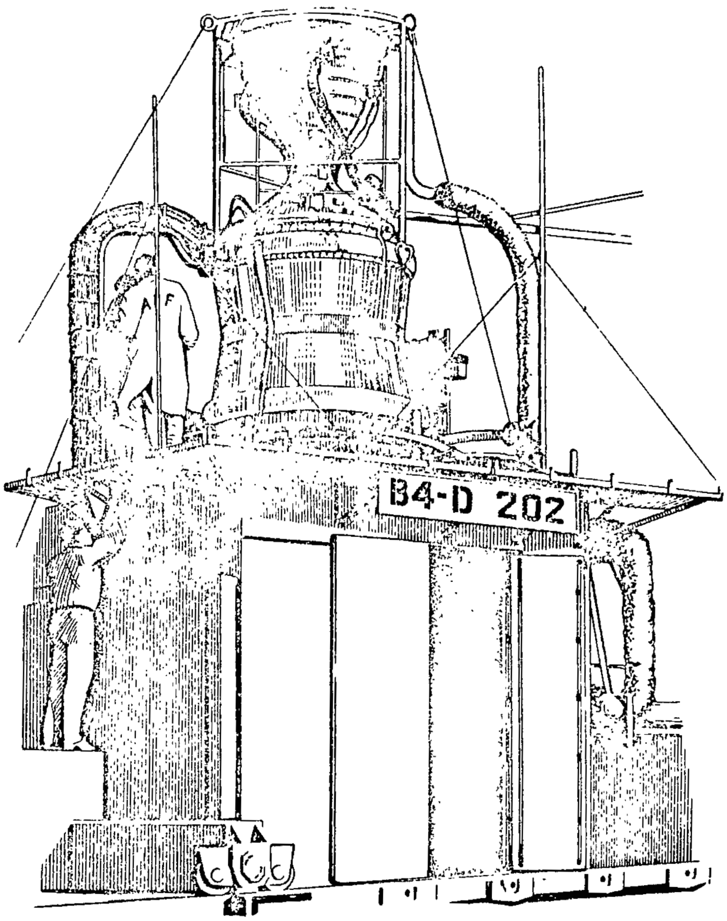


Fig. 16. Tests of the Nuclear Rocket Engine Kiwi B4-D.

rockets with minimum fuel consumption up to a velocity of about 3000/km/hr and lifts it up to an altitude of 25-30 km. This auxiliary stage will be fired and returned to the Earth. After it, the principal stage with the nuclear engine begins to operate. It imparts a cosmic velocity to the rocket and carries it to the Moon. This stage can provide for a "soft" landing on the Moon, where the gravitation is relatively low, the reverse launching onto orbit around the Moon, and reentry into the trajectory toward the Earth. Finally, the two remaining stages with LPRE aid in carrying out maneuvers on the orbit around the Earth and reentry. /96

Particularly great prospects are open for rockets with nuclear power units (NPU) which are launched directly from orbit or from an interplanetary station. In this case, it is also expedient to start up the nuclear engine after the auxiliary rockets equipped with small LPRE's tow the completely-equipped spacecraft to some distance from the base. The design of such a craft with nuclear power units, intended for studying Mars, was recently described in literature[18] (Fig. 17). Designed for a flight lasting 15 months (roughly 450 days), with a crew of 4 men, the craft weighs 400 tons during takeoff and is assembled on orbit around the Earth.

Four rockets with liquid propellant engines, with take-off thrust of about 700 tons and payload capacity of 100-tons each, are used during the assembling of the craft. It can be anticipated that this payload capacity will soon be attained. The first rocket puts the principal stage into orbit--a nuclear power unit which has dry weight of 59 tons and which uses a fast neutron reactor. The cabin, the four members of the expedition and the capsule are put on orbit simultaneously.

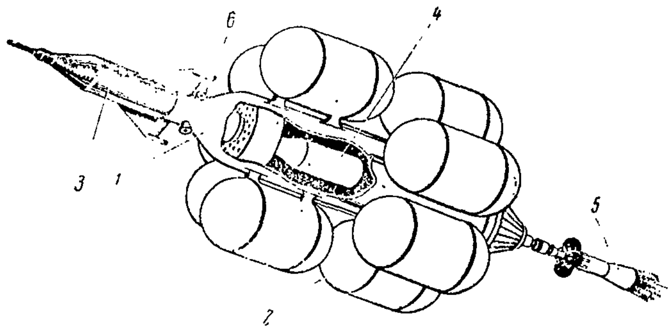


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Fig. 17. Craft With Nuclear Power Unit on Orbit Before Launching Toward Mars. (1) Principal Hydrogen Tanks; (2) Suspended Liquid Hydrogen Tanks; (3) Capsule-Module for 2 Men; (4) Crew Cabin; (5) Nuclear Engine; (6) Control Engines.

[18] Nuclear Rocket Spacecraft for Manned Exploration of Mars. Space World, A-1, Sept. Oct. 1963.

For protection from radiation and thermal effects, the cabin is encompassed by a double airtight envelope, which is coated by a film of graphite and is submerged inside the principal tank with hydrogen; the layer of hydrogen surrounding it is about 2.4 m.

An auxiliary nuclear turboelectric unit with power up to 50 kW is intended for providing the crew and equipment with energy. It is possible that it will obtain the heat from the principal nuclear reactor for the sake of economy of weight of the system.

Scientific equipment and instruments are put in the capsule. The capsule is equipped with the two stages with LPRE's which are necessary for landing two men on Mars and for subsequent boosting of the capsule onto the orbit, with it again hooked up to the nuclear stage.

After the successful entry of the principal nuclear unit onto trajectory around the Earth, the three remaining rockets transport 4 tanks apiece into orbit. Each of the tanks contains 20 tons of the working fluid--liquid hydrogen. Thus, there are 12 tanks on orbit which contain 240 tons of the liquid working fluid-hydrogen.

After assembly, the craft goes onto a trajectory moving toward Mars because of the operation of the nuclear engine. In this time, 6 of the tanks are used and 4 of them are ejected. The two tanks /98
remain as storage places in case of meteor bombardment.

At the end of the first part of the course, the apparatus goes into orbit around Mars with perigee of 320 km and apogee of several thousands of kilometers. Then the capsule with the two stages equipped with the LPRE's and the two crew members is separated from the craft. The retro engine apparatus and the aerodynamic deceleration in the atmosphere of Mars provides for a soft landing in vertical position. At that moment, the weight of the capsule is 16 tons. After 5 days of research, some of the equipment in the capsule is left on Mars in order to lighten the takeoff, and the last of the stages with LPRE's provides for launching on orbit toward the nuclear craft. After connecting with the craft, the crew walks from the capcule to the principal cabin, the capsule is ejected, and the craft takes off toward the Earth. At this time, the two subsequent external tanks are emptied. The working fluid is preserved during the entire course only in the forepart of the principal tanks as a shield against the radiation. In the vicinity of the Earth, deceleration is carried out with the use of the nuclear engine, while reentry into the planet's atmosphere is accomplished with the aid of one more capsule.

The Mars landing module proposed in the plan has been developed very schematically. Its greatest diameter is 6.5 m, and the length is 3.5 m. It is of a conical shape and is divided into 3 pressurized sections. The workshop and storehouses are installed in the lower section, which is equipped with an airlock for transferring onto the Mars surface, the living quarters are in the middle section, and the observation posts and observatory are in the upper section. The upper section is also equipped with a lock in order to guarantee hook-up with other stages of the apparatus. The wheeled landing gear is drawn inside the chamber.

An adapter in which the power unit for correction over the trajectory, the radiators and the antenna are mounted is fastened in the lower part of the capsule. The total weight of the capsule with the adapter is 25 tons, while the weight of the adapter is 7-9 tons. The capsule should move along the surface of the planet at a speed of 15 km/hr. The high conical shape and wheeled landing gear complicate movements if this surface is uneven; a caterpillar structure would be more practical.

It has been proposed that, for further mastery of knowledge on Mars during the first landing expedition, it is important to find the nature of the surface, the presence of minerals, plants, /99 water; it is also important to find whether or not the vegetation on Mars can be converted into food, or, in the extreme case, whether or not it can serve as a fertilizer for terrestrial plants in their cultivation on Mars.

## Electric Rocket Engines

The idea of a rocket engine is usually connected with a combustion chamber in which a violent chemical reaction producing a flux of incandescent gases occurs. Actually, in the combustion chamber of a rocket engine operating on a chemical fuel, the gases are strongly heated, and then their thermal energy converts into dynamic-kinetic energy during expansion in the nozzle.

The highest temperature which can be attained in combustion of a chemical fuel is close to 5000°. Correspondingly, the exhaust velocity caused by thermal expansion in the nozzle cannot exceed 5.5 km/sec. If there could be a further increase in the temperature of the gas, their exhaust velocities would also increase. This could be done by heating the gas with extraneous sources of energy, for example, with an electric current. Moreover, the material particles can be accelerated by other methods. For example, when the particles have an electric charge, they can be accelerated by applying an electric field or, if they have electric conductivity, by applying electric and magnetic fields.

The charged particles also serve as the working fluid for the so-called electric rocket engines, i.e., those in which, in addition to the temperature, guaranteeing the supply and preliminary acceleration of the working fluid, electric and magnetic fields are also used for its acceleration. This acceleration method is incomparably more refined.

The electric rocket engine is the brother of acclerators of charged particles, which are so widely used in nuclear physics in our atomic age, but the accelerator moves and uses itself to produce the thrust. Since the exhaust velocities which the accelerators impart to the ions and plasma are great, the specific thrust and proposed final flight speeds of the "plasma craft" can be very high. /100

That is why there are more and more reports appearing in the international press on electric rocket engines.[19] The authors of these reports consider that the use of such engines will aid in reducing the takeoff masses of the crafts to suitable values. In using chemically propelled engines, they are extreme even for voyages within the boundaries of the solar system.

A distinguishing feature of electric rocket engines is the very low ratio between the absolute thrust and the weight. Therefore, the characteristic aspect of the electric engine is its capacity to break away from the ground. However, when this engine is transported by an ordinary rocket system onto a cosmic orbit, it could then act successively both in the orientation system and for gradual acceleration of the spacecraft up to very high velocities.

The use of electric rocket engines operating in flight aids in correcting the errors allowed during takeoff and shortening the flight time. For example, flights toward Saturn on a rocket with an ion engine require roughly half the time (around 2 1/2 years) than that from a rocket with an engine which uses a chemical propellant.

A comparison was made between the takeoff weights of two multistage rocket apparatus with engines operating on a chemical fuel (hydrazine fluoride), which flew from the surface of the Earth to an orbit around Mars, with a delivery of a load weighing 2.6 tons, and back to orbit around the Earth in 12 months. One of the rockets differed from the other in that its last stage, weighing 4.5 tons, had an electric rocket ion engine with a source of 275 kW power. It was shown that this guaranteed a flight with a takeoff weight of the entire system 4 times less than the weight of the system without the electric rocket stage. Correspondingly, the cost of the combined rockets is 8 times less than what is allowed for developing the electric rocket engine.

[19] See, for example: Missiles and Rockets, Vol. 6, No. 9, p. 21, 1960; Aviation Week, Vol. 70, No. 26, pp. 47-48, 1960.

In addition to increasing the absolute thrust, the designers of electric rocket engines are preoccupied with the problem of increasing the thrust from a square meter of the area occupied by the output section, the engine nozzle. Let us remember that the liquid propellant rocket engine can produce more than 50 tons of thrust over each square meter of the output section of the nozzle. The electric rocket ion engines still produce less than 1/1000 of this thrust per square meter of their output section. Multicell electric rocket engines, representing a combination of a large number of engines distributed as compactly and closely as possible, are being developed for this. A study of the reciprocal effect of such closely-distributed beams or streams of particles producing the thrust is one more problem with which the designers of new engines are occupied.

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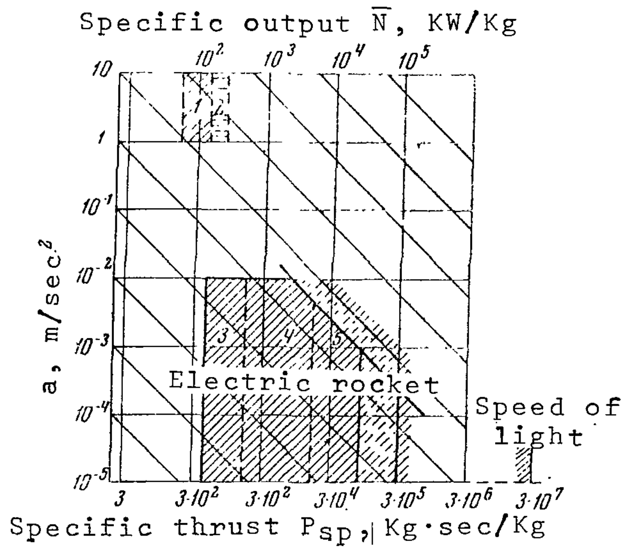


Fig. 18. Specific Electric Output Necessary for Accelerating the Jets, as a Function of the Specific Thrust (Impulse). Regions of Optimal Specific Thrusts for Several Types are Isolated: (1) Thermochemical; (2) Atomic; (3) Electrothermal; (4) Plasma; (5) Ion.

The electric rocket engine requires electric energy in order to obtain the working fluid and produce the thrust. Therefore, a power plant which aids in converting the thermal energy into electric energy should be found on the craft. The electric energy is then converted into kinetic (dynamic) energy of the particles spouting from the engine. /102

It is well known that it is desirable to obtain the highest possible specific thrust and the highest exhaust velocity of the working fluid for chemical engines. The situation is different for electric rocket engines. The reason is that the working fluid and power source are separated from each other in such engines.

Theoretically, the electric rocket engine can provide for a very high specific thrust--more than $10^5$ kg·sec/kg (Fig. 18). The specific thrust is directly proportional to the velocity of the ejected working fluid. However, the specific power necessary for accelerating the jets increases in proportion to the square of its velocity, and, together with the power, is roughly proportional to the square of the velocity of the working fluid, and the weight of the power unit increases.

It is obvious that we must pay for the increase in specific thrust and decrease in the weight of the reserve of working fluid with an increase in the weight of the power unit and a complication of its structure. The specific thrust should be selected as such that the total weight of the energy unit and working fluid is the least possible.

Consequently, the exhaust velocities and specific thrusts on electric rocket engines should not always be the highest. The lowest weight of the apparatus is attained when the weight of the power units and that of the fuel reserve are roughly equal. As a result, the value of the specific thrust for which the best flight data are obtained is determined for a certain weight of the entire power unit is kilowatts of the output "released" by it as a function of the course of the flight.

For physicists who are occupied with accelerators, this primarily gravitational analysis or selection of the accelerating system appears to be unusual and the optimal velocities of the exhaust from the engines of the spacecraft appear to be low. Actually, as follows from calculations, the specific thrust (value roughly 10 times less than exhaust velocity) is from 1500 to 5000 Kg·sec/Kg for relatively short flights, and from 7000 to 50,000 kg·sec/kg for interplanetary flights. /103

Since relatively high electric outputs are needed in order to attain such specific thrusts and the corresponding particulate velocities, the total amount of particles accelerated in the propelling agents, and thus the absolute thrust of the electric rocket engine, are low.

The electric power consumed by the engine is equal to the kinetic energy of the outflowing jets, with a consideration of the efficiency $\eta_g$:

$$N_e = \frac{m_{sec} v^2_{w.f}}{2\eta_g}, \qquad (2.7)$$

where $m$ is the consumption of mass of the gas/sec.

It is well known that the engine thrust is equal to the product of the mass of gas consumed per sec times its velocity, i.e.,

$$P = m_{sec} v_{w.f.} \tag{2.8}$$

Consequently, the power, thrust, and exhaust velocity are connected by the following simple relationship:

$$N_e = \frac{P v_{w.f.}}{2\eta_g} \tag{2.9}$$

For example, when the power is 5000 kW = $5 \cdot 10^6$ W, the exhaust velocity is 100 km/sec = $10^5$ m/sec and $\eta_g = 0.5$, and the engine thrust is 50 newtons in all, which is roughly equal to 5 Kg. The mass of the entire unit with the power plant and reserve or working fluid is $M$ = 50,000 kg for a specific weight of $\gamma$ = 10 kg/kW.

The thrust of electric rocket engines is very low compared to their weight (mass). The thrust-weight ratio is usually less than 1/1000; therefore, the electric rocket engine can be used for space flights only where there is no substantial atmospheric drag, in regions where the gravitational forces are low and the acceleration of the force of gravity does not exceed $10^{-4}$ m/sec$^2$. In the example examined above, considering Newton's law $P = Ma$, we find that the acceleration of the apparatus is $a = 10^{-3}$ m/sec$^2$.

Electric rocket engines can be divided, in terms of the nature and method of acclerating the working fluid, into electrothermal, electromagnetic and electrostatic engines (Fig. 19).

In electrothermal engines, the gas jet is accelerated by its thermal expansion in the nozzle. Thus, they are virtually thermal engines, but with very high gas temperatures obtained by electric heating. /104

In electrostatic engines, the ions and electrons of a plasma are preliminarily separated, and only then the ions are accelerated by an electric shield, with their subsequent neutralization by the electrons when going out of the engine nozzle.

Finally, in electromagnetic engines, the acceleration of the "undivided" plasma--a quasinettral mixture of electrons and ions--is achieved by applying intersecting alectric and magnetic fields on it or a magnetic pressure.

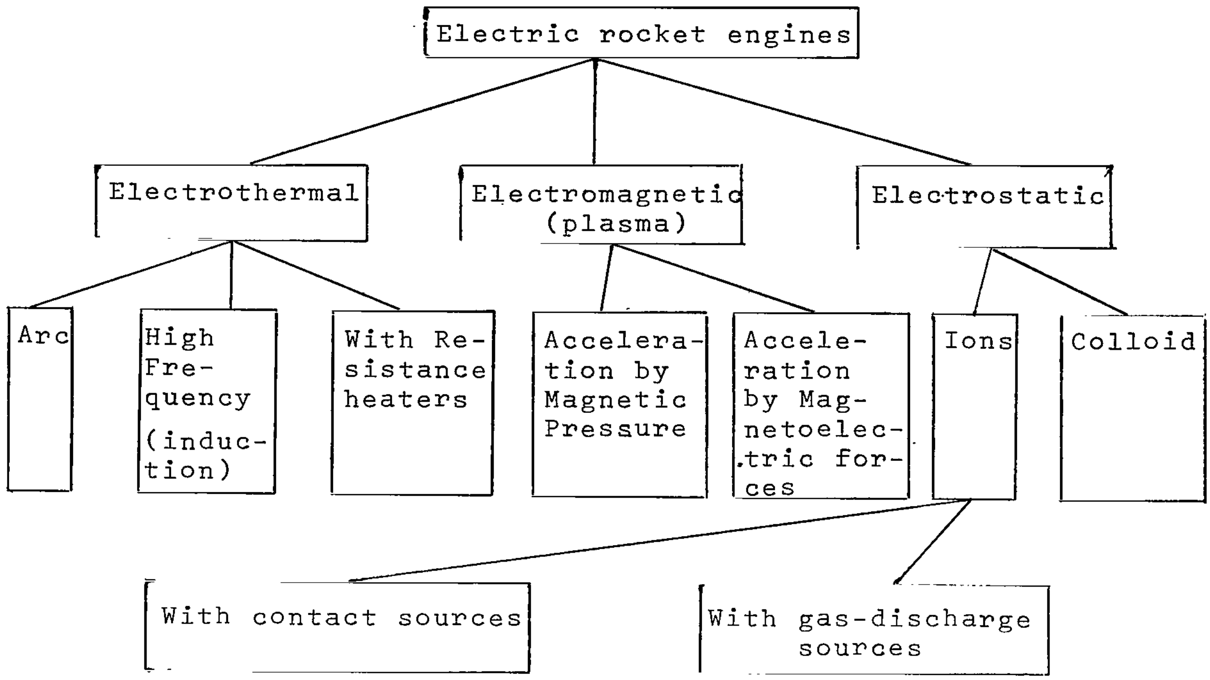


Fig. 19. Classification of Electric Rocket Engines.

We should mention that, depending on the plasma temperature, plasma engines can produce a thrust as a result of different physical processes occurring in the working fluid. The thrust is obtained at relatively low temperatures by direct electromagnetic acceleration and ejection of the particles composing the plasma jets. At very high temperatures, some of the thrust can be produced by light (quantum) emission. It is assumed that, at a temperature of $15 \cdot 10^{4\circ}$, the plasma can be emitted as an absolutely black body. If the energy injected into the plasma is used only for emission in this case[20], while there is no consumption of the plasma from the engine, the light pressure can become substantial in the total balance of the thrust. /105

All the cited types of electric rocket engines can be divided into the following groups in terms of the method of obtaining the

[20] Let us remember that, if we could obtain a thermonuclear reaction in the plasma itself, energy would be released because of decrease of only roughly 1/100 the mass of the substance taking part in the reaction. We can also assume that the energy is fed to the plasma from an external source.

working fluid: electrothermal engines can be divided into arc and high-frequency engines and those with resistance heaters; the ion engines can be divided into systems with contact and gas-discharge sources; plasma engines can be divided according to the method of accelerating the plasma into systems with acceleration by intersecting magneto-electric fields and systems with acceleration by a magnetic pressure.

The structural and theoretical characteristics of electric rocket engines reverse the situation so that the electrothermal engine guarantees a specific thrust no higher than 1500-200 kg·sec/kg, the electromagnetic (plasma) engine has thrust up to 15,000 kg·sec/kg and, finally, the ion engine goes up to 60,000 kg·sec/kg. These figures also limit the range of their application, since it is more advantageous to use a simpler engine when necessary, for low specific thrust (and, consequently, light power units) and for relatively short flights.

Thus, these engines types compliment each other very well.

Electrothermal Engines. The prototypes of electrothermal engines, the so-called plasmatrons, appeared more than 40 years ago. They were electric arcs with water stabilization. The most refractory metals flow through by the effect of a plasmatron jet, and it cuts through apertures in the most heat-resistant ceramic blocks.

The heat resistance of materials has been studied extensively /106
with the aid of plasmatrons during recent years. Even a few years ago, plasmatrons were used as high-temperature torches for welding and cutting metals, for depositing high-temperature coatings. They are also used for air flow on test stands for the noses of rockets. In this case, the plasmatron is used to obtain temperatures of several thousands of degrees for several minutes.

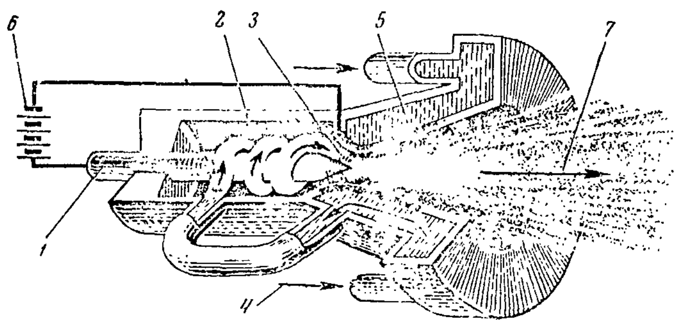


Fig. 20. Electric Arc Plasmatron.
(1) Cathode; (2) Arc Chamber; (3) Arc; (4) Working Fluid Feed; (5) Anode; (6) Feed Source; (7) Jet Stream.

The electrothermal engine with electric arc plasma generator--plasmatron (Fig. 20)--consists of a chamber with central electrode-cathode and cylindrical anode.[21] The cathode can be made in the form of a rod with automatic supply to compensate for the material carried away by the arc, and to sustain the gap between the electrodes. This distribution of electrodes in the arc can decrease the heating zone and alleviate the conditions for cooling the electrode. The electric energy is used for an increase in the temperature, as well as for ionization and dissociation (splitting) of the molecules.

The liquid or gaseous vortex flow of the working fluid passing into the channel between the cathode and anode protects the walls of the chamber from the high temperature obtained in the arc, and cools its upper surface. The cooling decreases the electric con- /107 ductivity on the periphery of the plasmatron chamber. As a result, the current and energy release of the arc are stabilized and concentrated in its central section, which makes the arc several times hotter than when there is no vortex. The heated gas is accelerated in the nozzle mainly because of thermal expansion. Modern plasmatrons provide for a temperature up to $5 \cdot 10^{4\circ}$.[22]

One of the basic disadvantages of the electrothermal engine with electric arc heating is the small reserve. The working fluid ejected contains particles of the electrode materials, and causes erosion of the apparatus in the region of the jet stream. The use of a porous anode and special protective coatings of the nozzle, and a decrease of the pressures of the chamber, aid in increasing the reserve of the engine. There are now engines which have a monthly operational resource.

According to several authors[23], a specific thrust of $3 \cdot 10^3$ kg·sec/kg and efficiency of 50% can be attained in an electrothermal engine with a resistance heater by using a tungsten heating cell and hydrogen as a working fluid. This is a very simple design; however, it has low resource. Alkali metals (lithium) can also be used as the working fluid.

Heating in a plasmatron can also be accomplished by high-frequency currents (Fig. 21) in the tube-core of an induction coil. The gas is then accelerated by thermal expansion. Obviously, the high-frequency plasma source is heavier than the electric arc source, since the conversion of electric energy into high-frequency

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21 See: "Astronautics", VI, 1962; "Scientific American", III, 1961; "Interavia", 10, 1958.

22 See: Izobretatel i Ratsionalizator, No. 2, 1960.

23 Space Astronautics, Vol. 1, 1963; Missiles and Rockets, Vol. 29, No. IV, 1963.

energy requires that the supplementary equipment have more weight. The auxiliary units also decrease the reliability of the system. Some of the electromagnetic energy is emitted in vain by the coil into space, worsening the efficiency.

The advantage of an electrothermal engine with high-frequency heating is that the gas can thus be heated up to high temperatures in the axial section of the plasmatron without contact with the electrodes. The plasma is isolated reliably by a cold gas or liquid film from the walls, the resource of their plasmatron is greater, and the heat losses on the walls are low. /108

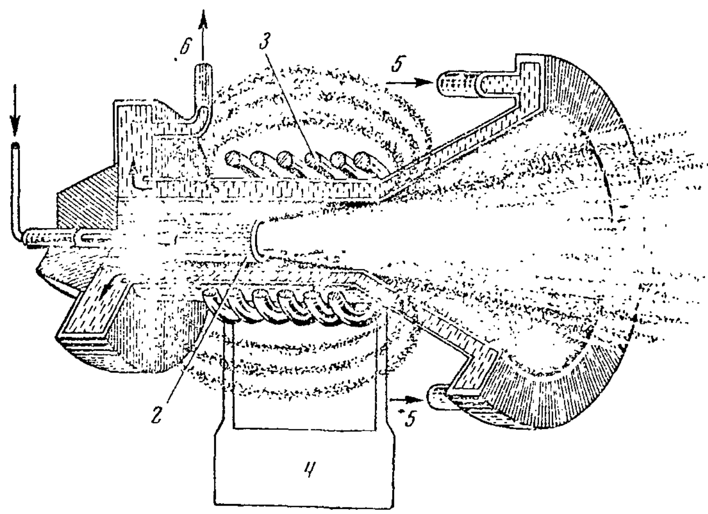


Fig. 21. High-Frequency Plasmatron. (1) Gas Feed; (2) Body of the Generator; (3) High-Frequency Coil-Solenoid; (4) Supply Source; (5,6) Lead-in and Tap for the Liquid to Cool the Nozzle and Body of the Generator.

Finally, we should mention that the electrothermal engine is simpler in design and lighter than the other electric rocket engines. At the same time, the exhaust velocity which it can attain is less; therefore, according to (2.9), it will develop greater thrust and greater acceleration of the apparatus, but the working fluid will be consumed more rapidly, for identical power. Therefore, the electrothermal engine is suitable only for comparatively short-range flights.

The designing of an electrothermal engine with specific thrust of 1100 kg·sec/kg was reported in the Foreign Press.[24] One of the engines, which operates on hydrogen and helium, developed a thrust of 340 *g* for a weight of 1.6 kg and power of 30 kW, and the other developed a thrust of 450 *g* for a weight of 4.5 kg. Models with output of 300 kW are being developed. /109

Electromagnetic (Plasma) Engines. We all know that matter exists in three states: solid, liquid, and gas. Recently, more and more attention has been given to a unique fourth state of matter, which is called a plasma.

The atoms and molecules in a solid are arranged in a definite order. It is extremely difficult to break down or shift this order. In a liquid, they have greater, but nevertheless limited, freedom of motion, since the intermolecular distances and the volume of the liquid almost do not change. In a gas, the molecules and atoms move freely, but all the electrons inside the atoms move along their own orbits. In a plasma some of the electrons of the outer shell separate from the atoms and acquire complete freedom of motion. The atoms and molecules, losing some of the electrons, acquire a positive electric charge and become ions.

The state of a substance for which one or more electrons break away from some of its molecules or atoms is called a plasma. This substance is, as a whole, an electrically neutral mixture of positively hcarged particles-ions, fragments of molecules or atoms and free electrons.

Both free electrons and ions can carry an electric charge; therefore, a plasma is a conducting gas.

To operate an electric rocket engine, it is necessary first of all to obtain a plasma. Nature itself can show people how to do this, plasma is formed in the atmosphere where lightning passes through; this means that electric discharges in a gas can be used in order to obtain it. Plasma also appears in traces of heated meteorites; this means that it can be attained in a laboratory, for example, by heating gases on the porous surface of a metal. Plasma is formed in stars as a result of nuclear and thermonuclear reaction. This probably means that it can also be obtained in a nuclear reactor.

To obtain a plasma, it is desirable to select those substances which are ionized at the lowest temperatures, have high density (which allows us to make the tanks of the apparatus compact) and

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[24] Astronautics, VII, 1960; Interavia, III, 1962; Space Astronautics, I, 1963.

occur in relatively great abundance.

Let us boil one of the alkali metals in a vessel and direct the vapor formed through a tungsten grid heated to a temperature of 800-1000°. /110

The molecules touching the grid are excited and "lose their strength"; as a result, many of them lose their electrons, which are deposited on the grid. Ionized atoms -- ions of the alkali metal--break away from it. We not only obtain a plasma, but we divide it into ions and electrons. Since the plasma, or more precisely, the charged ion beam was obtained with relatively low heating of the lattice, this source can be called a cool one.

A plasma can also be formed if an electric arc is heated in a space filled, for example, with the vapor of an alkali metal. We will call this plasma source a hot one.

A great deal of ingenuity is needed to obtain a plasma. Then the working fluid obtained with such difficulty must be ejected from the engine nozzle, and, moreover, at a high speed.

The design of a plasma accelerator with external intersecting, "crossed", electric and magnetic fields is the most classic. It is represented in Fig. 22. In this case, the direct-current conductor--the plasma (the current passes from one bus-anode to the other cathode)--moves across the magnetic field acting on it, intersects the accelerator across the plane of the pattern and penetrates into the plasma. As a result, a force perpendicular to both crossed fields acts on the conducting medium, or the plasma, which should be heated up to 3000°. The operation of electromagnetic pumps, which are widely used for supplying liquid metals, is based on the same principle.

In the case under investigation, the unique electromagnetic "plasma pump" continuously ejects a fountain of the plasma, the jet stream of which also produces the jet thrust.

Most of the corresponding studies first investigated these linear discharge tubes. However, the high temperatures in the long thrust chamber (a short one does not allow the requisite acceleration) and the cooling of its walls and electrodes to prevent burn-out consume a great deal of useless energy. Heavy mag- /111
netic systems with cooled coils complicate the problem even more.

Therefore, it is of interest to examine the designs with natural magnetic and electric fields, where the requisite intensity of the magnetic field is obtained by the great force of the current in the discharge. The thrust chambers then become shorter, and the cooled magnetic systems do not have to be there at all.

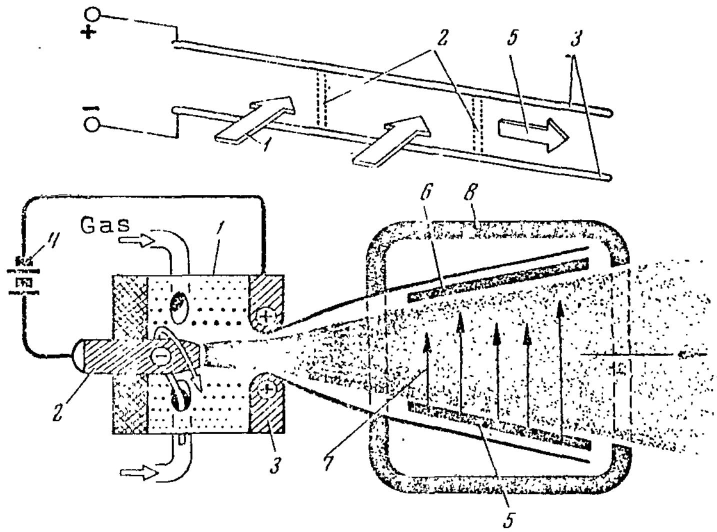


Fig. 22. Plasma Engine With Crossed Magnetic and Electric Fields. Top-Basic Schematic Diagram of the Action of the Accelerator (1) Magnetic Field; (2) Electric Arc in Plasma; (3) Electrodes; (4) Supply Source; (5) Direction of Movement of the Jets; Bottom--Schematic Diagram of Engine (1) Plasmatron Body; (2) Anode; (3) Cathode; (4) Plasmatron Feed Source; (5) Anode of Thrust Chamber; (6) Cathode of Thrust Chamber; (7) Direction of Electric Current; (8) Coils for Producing Magnetic Field.

It is a complicated task to obtain such high currents, and they are still being obtained for a very short time in laboratories, because of the discharge of the capacitor batteries. However, a rather powerful high-current source of electric energy can also guarantee continuous operation. /112

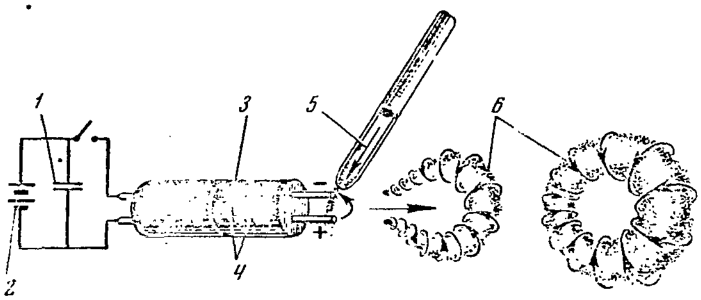

Fig. 23. Plasma Engine With Acceleration of the Working Fluid by Magnetic Pressure. (1) Capacitor; (2) Discharge Current Source; (3) Insulator; (4) Electrodes; (5) Working Fluid Vapor Stream; (6) Plasmoids.

Let us describe the apparatus in which plasma acceleration can be obtained only by the natural magnetic field produced by currents which pass over the plasma, i.e., by the magnetic pressure. This phenomenon appears, for example, during the development of plasmoids--conducting plasma rings with current. In 1941, G.I. Babat in Leningrad designed a plasma gun which imparted a high velocity to plasma rings[25] by the discharge of a capacitor battery.

The design of one of the engines of this type (Fig. 23) is named after the specialist who proposed it, the "Bostik gun", or as is usually said, the "button gun", and its entire appearance justifies this name. This accelerator is very similar to a small button made of an insulator and stitched with conductors. Some of the molecules of the working fluid pass into the space between the two electrodes, are condensed, deposited in the space between them, and seal it. The effective voltage is supplied at this moment. An electric arc appears in the melting zone. The working fluid in the gap between the electrodes is ionized, from which a cloud, or a plasma bunch, is formed. A high-power current dis- /113
charge appears in the transverse magnetic field of the same current, which passes over the electrode. The magnetic field compresses and ejects the plasma along the gap at a speed from $2 \cdot 10^4$ to $4 \cdot 10^4$ m/sec. The outgoing plasma bunches are "compressed" by the magnetic lines of force into closed eddying "boubliks"--rings or plasmoids similar to those blown by a smoker.

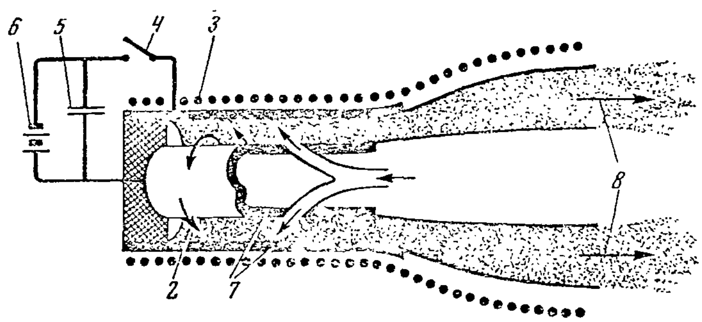


Fig. 24. Plasma Engine--Shock Tube With Acceleration of the Working Fluid by the Magnetic Pressure. (1) Gas Feed; (2) Loop of the Electric Current Producing the Thrust; (3) Coil of Magnetic Field (4) Current Breaker; (5) Capacitor; (6) Feed Source; (7) Cylindrical Electrodes; (8) Direction for Gas Outflow (Discharge).

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[25] See: Tekhnika-Molodezhi, No. 3, 1963.

Plasma rings can also be obtained by an explosion-like discharge spark between the conductors, which brings about their evaporation. In such cases, it is recommended that the coating made of a substance with a low atomic weight which yields primarily light ions, guaranteeing that a steady discharge can be applied on the wire. However, this method is connected with expenditure of the electrodes. Therefore, we can use the design for feeding the working fluid described above, or we can obtain plasma bunches by fusing an additional wire which is supplied up to the point of intersection with the electrodes.[26]

Figure 24 shows one more design for an accelerator, with plasma acceleration due to the magnetic pressure. If the accelerator of this type operates on an impulse regime, it is often called a shock tube. The gas moves continuously into the cavity between the two cylinders. When the knife switch (4) is connected, a boublik-like current discharge arises between the cylindrical /114 electrodes (7). Depending on the dimensions of the capacitor discharge, this loop is accelerated by the effect of natural magnetic field of the current going over the electrodes perpendicular to the direction of the current in the discharge, and it pushes the gas ahead of it, like a piston. A shock wave arises and propagates in front of the current loop. The coils surrounding the cavity of the accelerator produce a weak axial magnetic field, which, on the one hand, prevents the withdrawal of the plasma on the wall, like a magnetic bottle, and consequently decreases the energy losses, and on the other hand, turns the discharge, providing for greater uniformity. The gas between the current loop and the chock wave is heated and acquires directed movement.

In the accelerator roughly half of the energy supplied converts into kinetic energy of the gas and the other half converts into thermal energy. The expanding nozzle allows some of the thermal energy of the gas to be used supplementarily to increase its velocity.

Combined accelerators are also being produced, in which the magnetic field arises due to the current passing over the outer coils, and due to the natural field of the current on the electrodes, and it interacts with the currents inside the plasma. These devices include accelerators with a rotating plasma and with crossed fields.

The accelerator of a rotating plasma does not differ in design

[26] See: Kask, S., W. Starr. Manual Meeting of the American Rocket Soc., Nov. 16, p. 1008-1059, 1959.

from a shock tube (see Fig. 24) and can also operate on an impulse regime. The basic difference between them is that the outer coil (3) in this device produces a strong magnetic field.

The accelerator is also two coaxial cylinders divided by an insulator. The internal metallic cylinder of the "rotary accelerator" serves as the cathode, and the outer cylinder serves as the anode of the circuit.

A special winding which is fed by the current from an external source and which produces a strong magnetic field directed along the accelerator over the axis of the cylinders is arranged around the outside cylinder. The working fluid is supplied into the gap between the cylinders (for example, gaseous hydrogen). The electric discharge current is transmitted across the accelerator from the outer cylinder to the inner one. As a result of the discharge in the partially ionized gas, free electrons and a natural magnetic field "frozen" in it appear. By the effect of these two fields, the electrons of the partially ionized plasma twist intensively around the axis and ionize the plasma uniformly, so that all of this mass is involved in the rotation.

At the same time, by the effect of the field of the outer winding and the "frozen" magnetic field which is produced by the current passing over the electrodes and in the plasma, it is shifted and "drifts" along the axis of the accelerator and is ejected from the nozzle.

This system allows us to obtain very high exhaust velocities of the working fluid. However, its efficiency decreases, mainly because of the increased heat release in the electrodes.

The plasma accelerator with curvilineal jet electrodes, which is based on the so-called electromagnetic pinch effect, is being investigated more and more extensively at present.

The first experimental studies with accelerators of this type were carried out for physical purposes by the Academicians I.V. Kurchatov and L.A. Artsimovich.

What is the effect like? After a discharge arises in the gas filling the cylindrical space between the two round electrodes (Fig. 25), the current is concentrated in a thin cylindrical film on the outer surface of the gas. Interacting with the longitudinal current in the gas, the magnetic field arising around the film compresses the gas column as if into a narrow tube directed toward the axis of the electrodes. The discharge seems to constrict itself. A strong shock wave arises in the direction toward the axis of the electrodes, and the plasma is ejected from the aperture in the electrodes.

Figures 25 a, b and c show three successive positions of a self-constricted discharge moving toward the axis.

If we change the shape of the electrodes so that they form a nozzle, then the "reverse" reflection of the front of the shock waves from the axis of the accelerator will be negligible and the kinetic (dynamic) energy of the radial motion will be converted into energy of the longitudinal motion much more easily than in the case when the gas flows from the aperture along the axis of one of the electrodes. It is more convenient to convert the energy stored in the capacitors into dynamic energy of the ejected gas in at least six constrictions of the plasma during 1 discharge of the capacitors, which corresponds to three complete cycles of current alternation.

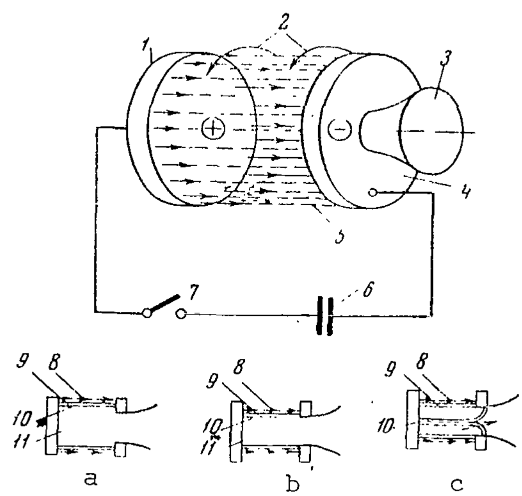


Fig. 25. Electromagnetic Pinch Effect in the Case of a Straight-Line Discharge Tube With Nozzle. (a) Beginning of Discharge; (b) Some Time Later; (c) Shock Wave Reaches Axis. (1) Positive Electrodes; (2) Magnetic Field on Surface; (3) Nozzle; (4) Negative Electrode; (5) Surface Currents; (6) Capacitors; (7) Discharger; (8) Magnetic Plunger; (9) Constricted Accelerated Gas; (10) Shock Waves; (11) Unaffected Gas.

Figures 26 shows the schematic diagram of an engine of this type with curvilinear electrodes, for which nitrogen is used as the working fluid. The capacitor is discharged with a voltage of 3000 V and, at the same time, there are four pulsed injections of the nitrogen. The group of four portions of the working fluid obtained is accelerated and injected through the nozzle as a single plasma discharge every 2 sec. This yields a thrust of about 5 g. The specific thrust obtained is up to 400 kg·sec/kg. The power which would be consumed to guarantee operation of this pro- /116 pelling agent for efficiency of 100% is 1 kW.

Finally, let us describe the traveling-wave accelerator (Fig. 27.) The plasma bunches, which are obtained in one of the sources we have described, for example, in a high-frequency source, are supplied into the tube of the accelerator. Magnetic waves arise along it because of the variable change in voltage produced in the coils surrounding the tube. Moving along the accelerator, they act like magnetic mirrors, which capture and reflect the plasma bunches in sequence. This accelerator is most similar to the "inside-out" electromagnetic gun, with which we began our story on electric rocket plasma engines. /117

We should mention that it is a complicated task to design light structures which guarantee the requisite nature of the voltage on the coils, as well as high-power energy accumulators. The traveling-wave accelerator surpasses all its comrade plasma accelerators in terms of the weight data.

In studying plasma engines and spacecraft on the Earth, the models and even the whole apparatus are put in vacuum chambers, where a low pressure simulating the vacuum of outer space is generated.

Reports in the foreign press indicate that thrusts from several grams to a kilogram and more and specific thrusts (impulses) 20 times exceeding those which can be obtained using modern liquid-propellant jet engines, can be obtained under laboratory conditions with the aid of plasma engines.[27]

Results have been published on a test of a model electric arc engine with power of 30 kW which operated continuously for 50 hours, ejecting helium and hydrogen at a velocity up to 16 km/sec. The engine thrust reached 300 g.[28]

V. Kh. Bostik reported on the construction of a pulsing engine with thrust of about 20 *g*, which ejected 100 plasma bunches per second at an average speed up to 10 km/sec.

Earlier (Fig. 26), we described a plasma engine with curvilinear jet electrodes, which discharged a plasma bunch every 2 seconds at a speed of 30-40 km/sec and produced a thrust of about 5 *g*.

A pulsing plasma engine with impulse of 9 *g* and frequency

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[27] Klass, P.: Aviation Week, Vol. 71, No. 23, pp. 76, 87, 89-90, 1959.

[28] Richard, J., J. Connors and Mironer: XIth Internat. Astronaut. Cong., Stockholm, 1960, pp. 232-245.

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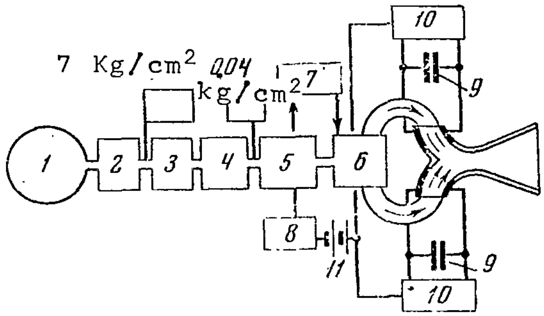


Fig. 26. Plasma Engine Using Pinch Effect. (1) Balloon With Working Fluid (Nitrogen), Volume of 1.7 cm$^3$; (2) Reducer Decreasing the Pressure to 70 kg/cm$^2$; (3) Filter With Apertures of 2μ; (4) Reducer Decreasing the Pressure by 0.04 kg/cm$^2$; (5) Nitrogen Chamber (Reserve); (6) Controlling "Lead-in" Valve; (7) Synchronizer of Nitrogen Feed Into Accelerator; (8) Command Controller; (9) Capacitors; (10) Discharger (Controlling Capacitor Discharge); (11) Electric Supply Source.

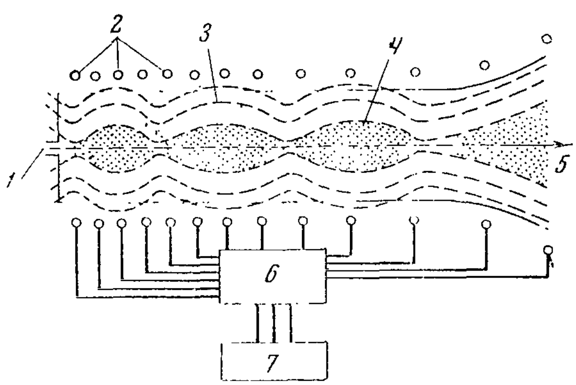


Fig. 27. Traveling-Waves Plasma Engine. (Diagram of the Action of the Accelerator). (1) Plasma Source (Feed); (2) Magnetic Coil Section; (3) Lines of Magnetic Field; (4) Plasma; (5) Direction of Motion of Magnetic Waves and Plasma; (6) Phase Control; (7) Three-Phase Energy Source.

of 17 Hertz was tested in a pressure chamber continuously for 60 hours.[29] One of the engines with continued flow developed a thrust up to 1.6 kg[30].

In December, 1964, it was reported that the first plasma engines in the world operated in space on board the Soviet automatic station "Zond-2". They guaranteed that position of the station at which the panels with the solar cells were turned toward the Sun and their luminance was maximal. The greatest amount of energy is transmitted to the instruments and equipment of the stations with such a position.

Electrostatic Ion Engines. Goddard mentioned in 1906 in one /119 of his notebooks that electrically charged particles can be used for producing a thrust. It was in 1911 that K.E. Tsiolkovskiy first published a suggestion on ways of producing electric rocket engines in general, and electrostatic engines in particular. E. Peltrey wrote of the possibilities of electric rocket engines in 1916. In 1915, the Polish researcher F. Ulinskiy proposed an ion engine operating on the use of solar energy. In 1923, H. Oberth wrote in more detail on the possibilities of using an "electric wind" to guarantee space flights in the book "The Way to Outer Space". A large number of theoretical developments followed. Naturally, ion engines have been most studied, compared to other engines of the future which are intended for obtaining very high velocities.

In 1954, E. Stulinger described the distinguishing features of ion engines and he suggested that a number of characteristics be introduced to evaluate the perfection of their structure. Developing Tsiolkovskiy's ideas, he suggested that Cesium and rubidium be used as the working fluid for the ion engines. These metals were selected because their atoms have comparatively high weight and are ionized well, since their outer electrons are weak- /120 ly connected with the atom. Compared to other alkali metals, cesium has the lowest melting point (35°) and heat of vaporization, the greatest density (1.873 g/cm$^3$) and the lowest energy of ionization (3.87 eV).

As we already mentioned, ion engines can be divided into contact-type and gas-discharge type according to the method of obtaining the working fluid or ions. The contact (surface) ion sources were studied particularly intensively in the first stage of developing ion engines.

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[29] See: Space Aeronautics, Vol. 37, No. 1, 1962; Aero Space Management, Vol. 4, No. 10, 1961.

[30] See: Astronautics, Vol. 7, No. 6, 1962.

The cesium or rubidium in this source is heated to evaporation and passes into the ionization chamber, where a heated grid (catalyst) made, for example, of porous tungsten, with diameter of the pores of 1-2 microns, is fixed (Fig. 28).[31] Tungsten has a substantial work function (4.5 eV). This means that it is difficult to "knock back out" the electron injected into it. Tungsten is heated up to a temperature of about 800° with the aid of a ribbon-like or spiral heater. During the passage (diffusion) of cesium atoms through the grid, the electrons tear away from them. The atoms are ionized and acquire a positive electric charge. In this case, the number of ionized atoms reaches almost 100%. The ions are then accelerated with the aid of an electrostatic field in the thrust chambers, where the natural vacuum of outer space reigns, up to velocities on the order of 80-200 km/sec. The electrostatic field is formed as a result of the supply of very high voltage to the accelerating electrodes (9).

The flux of ions should be focused well so that they do not fall on the accelerating electrodes, since this brings about intensive erosion--washing-out of the electrodes. The accelerating electrodes are latticed or laminated. They are usually grouped in multi-beam or multi-ring assemblies. A great deal of attention is given to the development of electrodes which form (8) and accelerate (9) the ion beam, so-called ion optics. Since particles of like charge repel each other, the density attained for their flux, which has space charge, is greatly limited, and the engine size must be increased. The velocity of the ions depends on the intensity of the field, and on the nature and magnitude of the gas pressure.

The stream of scattered ions must be neutralized when they flow out of the engine. Why must the ions leaving the rocket be neutralized? We must resort to this since, in ejecting only positive ions, the body of the apparatus would very soon be charged up to such a negative potential that a further ejection of ions would become difficult. By neutralizing the ions, we can also obtain a high density of the stream of working fluid flowing out of the nozzle.

One of the methods of obtaining a neutral jet is to have the stream of ions pass along a heated electrode-emitter (10) from which the electrons run off in it. A flux of repulsed neutral atoms is formed as a result. Another method is to obtain and accelerate beams of negatively charged particles (see Fig. 28b) in the engine together with beams of positive ions. These beams, intermixing and interacting at the output, also yield a neutral jet stream.

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[31] Boden, R.H.: Aero Space Engineering, Vol. 18, No. 4, 1959; Design News, No. 6, p. 17, 1962.

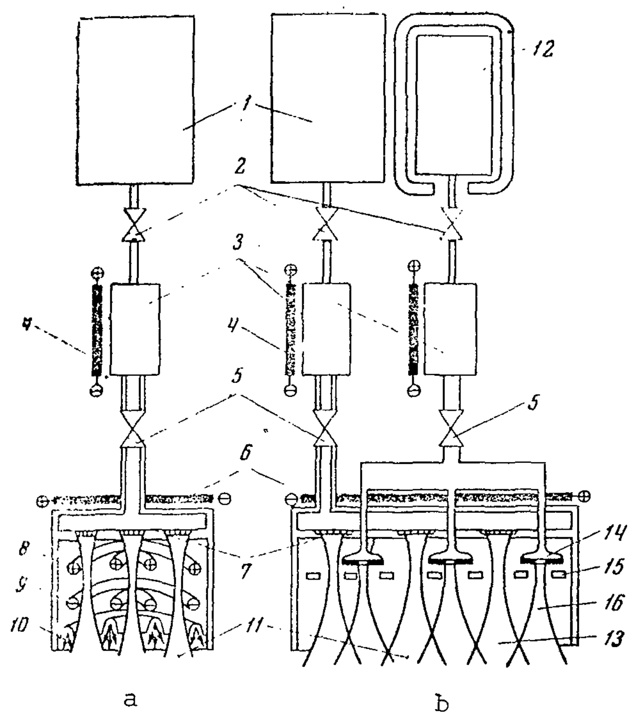


Fig. 28. Schematic Diagram of a Sectional Ion Engine.
(a) With Ion Source; (b) With Positive and Negative Sources.
(1) Cesium Tanks; (2) Rectifier; (3) Evaporator; (4) Evaporator Heater; (5) Rectifiers; (6) Ion Source Heaters; (7) Porous Tungsten Ionizers--Sources of Positive Ions; (8) Focusing Electrodes; (9) Accelerating Electrodes; (10) Neutralizing Electrodes; (11) Neutral Jet Stream; (12) Sulphur Hexafluoride Tanks; (13) Flux of Positive Ions; (14) Source of Negative Ions; (15) Zero-Potential Grid; (16) Flux of Negative Ions.

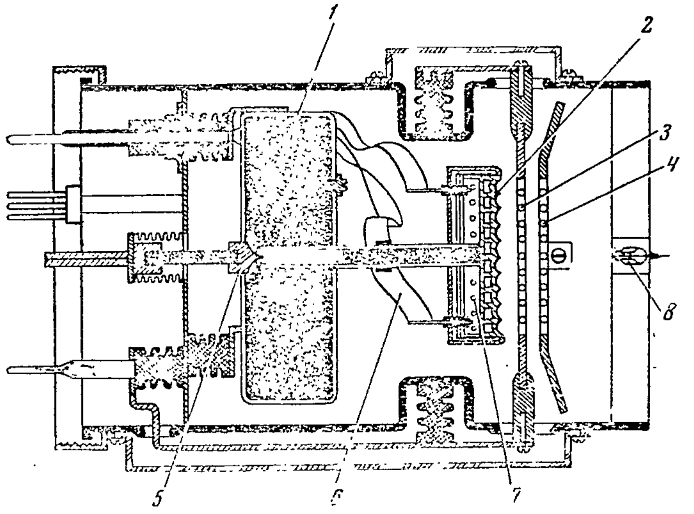


Fig. 29. Sectional Ion Engine. (1) Cesium Tank; (2) Ion Source (Porous Tungsten); (3) Control Electrode; (4) Electrode for Neutralization of Ion Beam; (5) Cesium Vapor Expenditure Regulator; (6) Contact Tape; (7) Ion Source Heating Cell; (8) One of 61 Nozzles for Ion Yield.

A schematic diagram of one of the multi-sectional ion engines /123 and the operation of its units are shown in Figure 29. The design of another ion engine is represented in Figure 30.

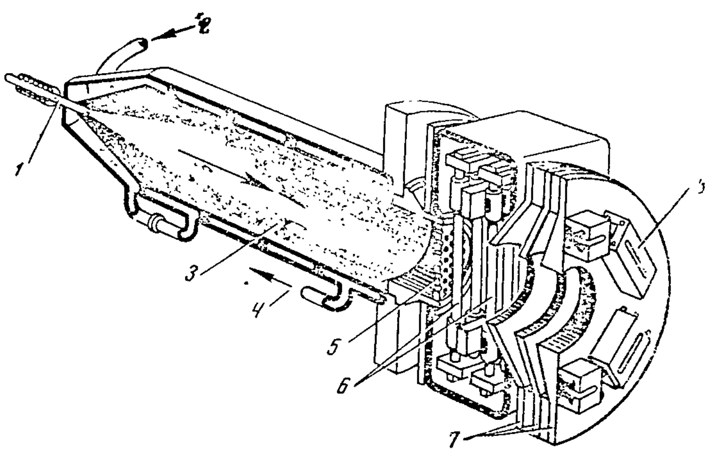


Fig. 30. Structure of One of the Ion Engines. (1) Cesium Input; (2) Oil Input; (3) Cesium Preheating Chamber; (4) Oil Output; (5) Distributor Plates; (6) Doublerow Ionizing Grid of Tungsten Electrodes; (7) Accelerating Electrodes; (8) Six Electron Guns--Neutralizing Electrodes.

The heated cesium vapor passes from the evaporator to the chamber. So that there is no condensation of the vapor in the chamber, it is equipped with a jacket through which the burning oil is pumped. The vapor passes from the chamber through the calibrated nozzle on the distributor plate (5) to the ionizer--a double row grid made of tungsten electrodes. The ions obtained are dispersed with the aid of the accelerating electrodes (7), pass by the neutralizing emitters (8) and are ejected from the engine. /124

The most important gaseous ion sources are sources with electron bombardment and the arc source-the von Ardenne duoplasmatron. In the electron bombardment source, the electrons are emitted or radiated by the cathode, just as the electrons in a cathode-ray tube. They are then held and formed around the cathode by the electric field in an oscillating electron cloud. The gaseous working fluid is injected into this cloud. The electrons bombard the gas atoms and ionize the gas. The ions obtained are accelerated by the electric field and ejected from the engine. The electrons in the cloud which have greatest energy are not confined around the cathode by the field, break away from the cloud and neutralize the out-going flux.

Since the electron neutralization of the ion beam occurs intensively, the engine under description is less subjected to the limitations on density of the stream than is the source with contact ionization. It can provide greater values for the thrust per unit frontal surface than the other electrostatic engines. Nitrogen, hydrogen, carbon dioxide, mercury and even the produces of man's respiration can be used as the working fluid.

The basic advantage of the other arc ion source--the duoplasmatron--is the possibility of successfully ionizing a number of elements (Fig. 31). For example, heavy ions of mercury, lead and bismuth can be obtained by using it. The high-energy arc is struck between the central and annular electrodes. The plasma is sent through the axial aperture of the central electrode. The arc is constricted by the external electric field. At high temperatures, numerous ions are generated in the plasma. The second annular electrode "extracts" these ions from the plasma. The ions thus extracted are then accelerated by the electric field. It is desirable that the extracted ions be concentrated in a small space and have identical initial velocity, so that they can be better focused.

It is considered that each fast ion which can break away from the flux and collide against the electrode surface knocks out up to 10 atoms from it. Therefore, it is necessary that the electrodes focusing the ion flux have a high focusing capacity. If even one /125
of each tens of thousands of accelerated ions falls on the electrodes, there must be a periodic replacement of the electrodes. The need for liquid cooling of the source and for producing an intensive magnetic field makes the source heavier. This is the same as the wear of electrodes of the duoplasmatron--the disadvan-

tages with which specialists are "quarrelling".

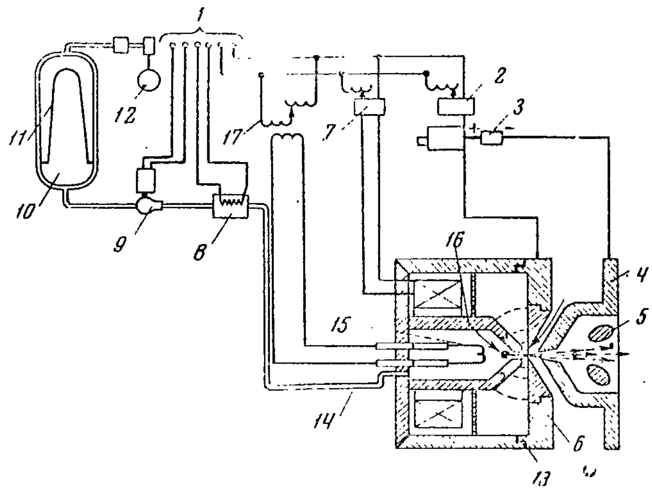


Fig. 31. Ion Engine With Duoplasmatron. (1) To Electric Energy Source (400 W, 100 V Direct Current); (2) Arc Feed (0-150 V); (3) Accelerator Feed (Electrode of Extraction System, 0-100 KV); (4) Accelerating Electrode; (5) Moderating Electrode; (6) Annular Electrode--Magnetic Circuit, 5000 Gauss in Gap; (7) Magnetic Feed; (8) Evaporator; (9) Pump With Electric Circuit; (10) Working Fluid Tank; (11) Elastic "Bag"; (12) Tank With Compressed Gas of the System Squeezing Out the Working Fluid; (13) Insulation (Mica); (14) Working Fluid Supply; (15) Filament; (16) Developing Plasma; (17) Filament Feed 30 a, 2.5V.

It has been stated that the least value for the specific thrust of ion engines is 750 kg·sec/kg, while the greatest value of the specific thrust which can be obtained for suitable weights of the apparatus and the ordinary instruments which convert heat into electric energy can go up to 20,000 kg·sec/kg. /126

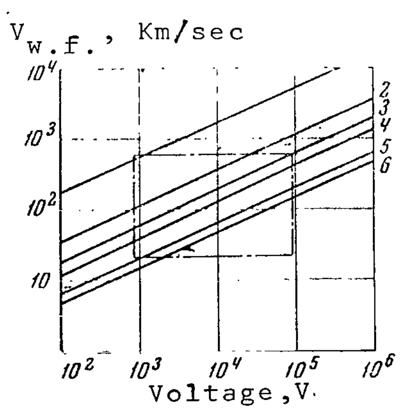


Fig. 32. Dependence of Exhaust Velocity of Working Fluid on the Magnitude of Accelerating Voltage and Mass of the Particles (The Dotted Lines Mark off the Range of Advisable Application of Ion Engines). (1) Hydrogen ($\mu$ = 1); (2) Sodium ($\mu$ = 23); (3) Lead ($\mu$ = 207); (4) Cesium ($\mu$ = 133); (5) Mercury ($\mu$ = 200); (6) Uranium ($\mu$ = 238).

The most suitable exhaust velocity can be found for each test carried out, depending on the design and purpose of the spacecraft. Figure 32 shows the dependence of the exhaust velocity on the accelerating voltages for a number of working fluids with constant mass.[32] The range of optimal exhaust velocities and accelerating potentials for the engines of orbital (from 20 km/sec) lunar and interplanetary apparatus (to 500 km/sec), corresponding to ion engines, is specially isolated. To avoid the danger of breakdowns, the accelerating voltage must be very high.

As can be seen from Figure 32, it is very convenient to use cesium for the ion engine. The use of working fluids with great mass would aid in decreasing the area of the thrust chamber. However, a method for ionizing the particles of "heavy" working fluids must be developed for this.

The disadvantage of the ion engine in comparison with other types of engines is that it is too bulky. However, if we consider the ion craft as a whole, this disadvantage does not seem to play too great a role. The power unit of the ion craft consists of two independent apparatus. One of them provides the electric energy, and the other serves as the engine and aid in preparing and subsequently accelerating the working fluid ejected from the chamber to produce the thrust. However, the bulk and mass of the ion craft are mainly determined by the power unit. /127

For an example, let us examine some designs of ion-drive craft.[33] Let us describe the plan in which a small automatic spacecraft--ion craft--is suggested for flying around the planets of the solar system (Fig. 33b).

The apparatus "solves" the tasks assigned to it, transmits information by radio and does not return to the Earth after this.

The weight of this apparatus, launching from the orbit of an artificial satellite, is 1.5 tons; of this, 100 kg are working fluid and almost 700 kg are payload (including the control instruments). The weight of the unshielded atomic energy plant and the electric system is 520 kg, and the weight of the body of the ion craft is 70 kg.

The section with research equipment should be moved out of

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[32] See: Voprosy Raketnoy Tekhniki, No. 17, 1959; No. 10, 1960

[33] See: Ross, D.P.: SAE Journal, Vol. 67, No. 7, pp. 40-42, 19 9; Kovacik and D.P. Ross: Nuclear Ion Rocket, SAE Journal, July, 1959; Aviation Week, X/22/1962.

the power unit on telescopic pivots. The instruments are protected from the radiation of the reactor (if only from one side). A nuclear reactor with heat capacity of about 1000 kW is suggested as the energy source of the engine. The heat from the reactor is led off with liquid sodium and sent into the mercury heat exchanger. The mercury vapor formed rotates the turbine of the electric generator, converting around 200 kW into effective electric energy. (It is difficult to have efficiency higher than 20% in such steam power plants.) The processed is then sent into the capacitor, where it yields its heat to the sodium preliminary passed through the radiators, which are necessary for driving out the excess heat, corresponding to power of about 800 KW.

The radiator-emitters should have a gigantic surface for discharging a large amount of the thermal power of the reactor and should be folded up before the apparatus is put into satellite orbit. They should be unfolded only when the ion engine begins to operate by the effect of the internal pressure. At the same time, the section with the research equipment is pushed forward.

The electric energy is used for pre-heating cesium up to a temperature of 900° and heating the tungsten grids on which it /128

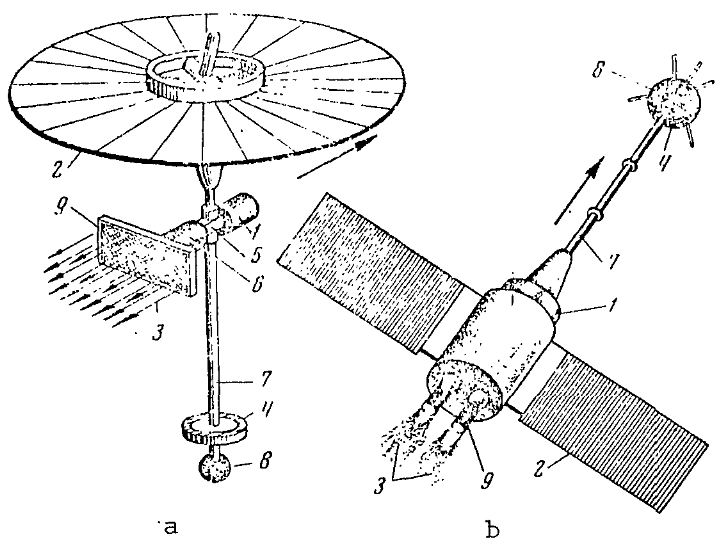


Fig. 33. Ion Craft With Disc "Umbrella" Radiator (a) and With Straight-Line Radiators (b). (1) Nuclear Reactor; (2) Radiator; (3) Particle Fluxes; (4) Protective Shield (From Radiation of t e Reactor); (5) Electric Generator; (6) Working Fluid Tank; (7) Structures for Spacing Different Parts of the Apparatus (Reactor and Space Laboratory); (8) Space Laboratory; (9) Output Section of Accelerator.

is ionized. Most of the power is consumed in the accelerator, where the ion flux acquires a velocity up to 200 km/sec by the effect of the electric field and flows out through the nozzle with the flux of electrons connected to it. The total attractive force of the two engines is only 0.15 kg (their specific weight is $4.7 \cdot 10^3$) and the apparatus can be imparted an acceleration of about 0.01% the acceleration of gravity on the Earth.

These negligible values for the thrust and acceleration can prove to be insufficient for long-range spacecraft. However, we must not forget that tens of seconds are used in boosting a "terrestrial" rocket with liquid-propellant jet engines, and it moves in the strong field of gravity of the Earth. The spacecraft will be much less attracted to heavenly bodies. Therefore, it gradually collects a substantial velocity even when the thrust is /129 this low.

As preliminary calculations show, the spacecraft (ion craft) should weigh around 730 tons during launching and have on board about 370 tons of working fluid in order to deposit a load of 150 tons on Mars. The engine system includes several thousands of sections and is located at the center of gravity of the craft between the reactors and the crew cabins. When the power of the electric generator system is 23000 kW, the engine in which the ions are accelerated by the effect of the electric field with voltage up to 490 V could develop a thrust up to 49.5 kg and impart an acceleration on the order of $7 \cdot 10^4$ m/sec$^2$.

The heat release necessary for condensation of the vapor behind the turbine might occur with the aid of a huge disk-radiator (see Fig. 30 a) with diameter of 115 m and a thickness of 6 cm at the center and 1 cm on the edges.

After reaching the highest velocity, the apparatus should be decelerated in the second part of the course toward Mars. The duration of a one-way trip (78 million km) is roughly 400 days.

Another original design for an ion-drive craft was published in 1959.[34] It is suggested that the electric energy necessary for heating its engine and the equipment be obtained from 200 heat converters installed on the surface of the reactor which produced an electric current with potential of 0.5 V when the cathodes are heated up to 2500°. Subsequent coupling of the cells produces 100 V. The reactor with power of 1000 kW should contain 200 kg of uranium carbide. Since it is suggested that the reactor be towed separately from the apparatus on a cable 1800 m long, this aids in decreasing its total weight, together with the radiation field, to 3.5 tons. The suggested acceleration of the system in space is about 0.001 m/sec$^2$.

[34] See: Husner, A.L.: Rocketdyne Report, 1959.

Another ion-craft design which has been developed and published has a power unit with output capacity of 1000 kW.[35] The suggested weight of the entire power plant is about 4 tons (specific weight of 4 kg/kW). The length of the entire system from the reactor to /130 the ion engine is about 9 m.

There are several loops in the system. Lithium circulates in the primary loop of the reactor-heat exchanger-pump. Its temperature is 1175°C at the output from the reactor. In the heat exchanger, the heat is released in four loops of the mechanical converters with power of 250 KW each. The coolant in these loops is potassium. Its temperature is about 690° at the input to the turbine. The area of the surface of the lobed cooler-radiator is about 160 $m^2$. In it, the temperature of the potassium is decreased to 590°, condensed and then again pumped into the heat exchanger.

Let us emphasize that it is difficult to discharge excess heat in outer space. When there is no atmosphere, the heat exchange due to convection--natural mixing of the heat-transferring gas when a cool gas replaces the heated gas at the surface of the capacitor--is impossible. Heat transfer can be accomplished only by radiation. The surfaces of the radiators are very large. That is why one of the most difficult problems in designing ion engines is to develop compact radiators-emitters. These radiators should be folded up before the apparatus goes on orbit and then expanded in space. It is also desirable that the radiator always be oriented edgewise toward the Sun. This allows it to give off heat much more intensively.

The requirements for protection from radiation have a great effect on the shape of the radiator. It is considered that the radiator should be placed in a shadow cone which is protected from the radiation of the reactor. Therefore, the radiator and the ion-craft itself acquire the shape of a cone or two-dimensional angle. In this case, the weight of the shield decreases and it becomes a single-edged shadow shield, not a round one (as in Fig. 33). The danger of re-emission, the reflection of radiation on the crew cabin from the wings of the radiator, is also decreased, since it is enclosed by the protective shield and is not radioactive.

Figure 34 shows the design of such an ion craft with a plane "beam" radiator and a shadow shield from the reactor.[36] When the power of the energy unit is 400 megawatts, it can bring three

[35] Megawatt Electric Power in Space. Astronautics, Dec., 1960.

[36] See: Voprosy Raketnoy Tekhniki, No. 10, 1964.

astronauts to Mars and back in 560 days, including a four-week stay /131
on satellite orbit. The landing rocket with liquid propellant rocket engine is intended for disembarkation from the satellite orbit to Mars and return to the ion-craft. There should be five craft and 15 astronauts taking part in the flight, and this increases the reliability and safety of the flight.

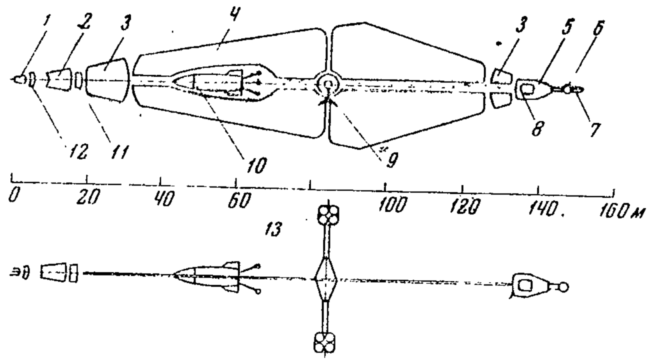


Fig. 34. Schematic Diagram of Ion-Craft With Shadow Shield. (1) Reactor; (2) Energy Converter; (3) Plant Cooler; (4) Principal Radiator; (5) Crew Cabins; (6) Control Section; (7) Orientation Instruments; (8) Radiation Shelter; (9) Ion Engine; (10) Landing Rockets; (11) Cesium Tank; (12) Shield; (13) Axis of Rotation to Produce Artificial Force of Gravity.

Reports have recently been published on laboratory tests of models of ion engines with load thrust which are intended for flight within the boundaries of the solar system or for controlling spacecraft.[37] One full-scale model of this engine type was demonstrated at the end of 1958. The engine had a cylindrical nozzle with length roughly of 60 cm and diameter of about 23 cm. Sodium tetrachloride, mercury, throium, cesium or rubidium can be used as the working fluid. The working fluid is preliminarily converted into gas and then sent into a chamber where a high temperature ionizing it is generated with the aid of an electric arc. After this, the ions are accelerated by the electrostatic field up to 130-180 km/sec. The engine thrust is roughly 115 *g*.

The ion engine shown in Figure 29 has thrust of 1 *g*, length of 34 cm, diameter of 10 cm and weight of 0.9 kg.[38] It has been

[37] See, for example: Aeroplane, No. 2461, p. 906, 1958.

[38] Astronautics, No. 1, 1961; Aviation Week, March 12, 1962.

reported that an engine with thrust of 230 *g* and ion velocity of 135 km/sec has been constructed. One of the engines operated for 50 hours, generating a thrust of about 300 *g* for specific thrust of 7750 kg·sec/kg; its reserve was estimated as $10^3$ hours.[39]

In 1964, an ion engine was tested on a ballistic trajectory, where it was brought by a rocket system with liquid propellant engine. The engine weight was equal to 5.3 kg, and the diameter was about 18 cm. The engine operated for around 20 minutes. For accelerating potential of $2.5 \cdot 10^3$ V, the thrust was around 3 *g*. The specific thrust reached $4.9 \cdot 10^3$ kg·sec/kg. The effectiveness of the method selected for neutralization of the beam was affirmed. It was shown that the presence of an ion engine in the apparatus did not produce interference in the radio communications. It is important that the exhaust velocities of the working fluid in such ion engines reach roughly 200 km/sec, i.e., velocities which are roughly 40 times greater than that which can be attained when using chemical propellants.

It has been said that a thrust of one $g/cm^2$ can be obtained when the accelerating potential is 40,000 V. In this case, a thrust on the order of 10 kg can be provided from each square meter of the jet stream section. For example, an apparatus weighing 100 tons can be imparted an acceleration of about $10^{-4}$ m/sec$^2$ when the area of the stream is 1 m$^2$.

The modern stationary accelerators in physics laboratories accelerate ions up to many tens of thousands of kilometers per second, but the intensity of the flux of scattered ions is still insignificant--millionths of a gram per second. At the same time, the accelerators themselves weigh tens and hundreds of tons. Even at those high thrusts which are necessary for ion-craft, the capacity of the accelerators must be increased, and their intrinsic weight must therefore be greatly decreased. The electric energy sources necessary for the operation of the thrust chamber in an ion-craft also weigh too much.

Thus, we can bring the designs of ion-craft to life after producing light, small and powerful ion accelerators and compact sources of electric energy. These apparatus should be easily con- /133
trollable, there should be no worries about damages from meteorites, and they should be adapted to operation in outer space for several years.

## Sailing Beneath the Sun

Almost 100 years ago, K.A. Timiryazev wrote that the energy of light is the motive power of the most complex plant of organic

[39] See: VDI-Zeitschrift, No. 12, p. 105, 1963

matter in a grain of chlorophyll. The force of a solar ray is conserved in the seed of a plant, converted into a hunk of bread, and, together with the latter, into the body of a human. It moves the arm of a laborer, the chisel of a sculptor, the hand of an artist, the pen of a poet and writer. But if we are all children of the Sun and we live and move by solar energy after most complex conversions, can we not induce the directed energy of solar radiation to move spacecraft?

The English physicist J.C. Maxwell (1931-1879) suggested that light is an electromagnetic wave. All electromagnetic waves consist of interconnected electric and magnetic fields and are propagated in vacuum at an identical velocity $c = 2.9976 \cdot 10^5$ cm/sec. However, the state of light in vacuum can be taken as equal to $3 \cdot 10^5$ km/sec in all calculations except for the most precise ones.

In 1901, P.N. Lebedev (1866-1912) showed experimentally that light can exert pressure on bodies. The magnitude of the pressure is determined by the angle of incidence of the rays on the surface and its reflectivity. But if light has a mechanical effect, can we not use this property to move spacecraft? It is true that the power of light pressure is very low. Solar rays would press with force of about 1 kg (or 1 kg/cm$^2$) on an ideally reflecting mirror with area of 1 km$^2$ on orbit around the Earth, and with half that power (0.5 kg) on an absolutely black body absorbing all the rays. As a result, it is found that solar rays press with force only of hundredths of a gram on the giant aircraft TU-114 flying in a cloudless sky, and with force of about 80,000 tons over the entire planet.

Solar pressure is an important factor which must be considered in calculating the trajectories of spacecraft. For example, the /134
shape of the orbit of the American satellite "Echo-1", which was a balloon with diameter of 30 m, made of polyethylene plastic and weighing 60 kg, was changed substantially by the light pressure.

The idea of using light pressure or the "solar wind" inflating the "sail" of spacecraft was first corroborated scientifically in calculations carried out in 1925 by the Soviet scientist F.A. Tsander (1887-1933). The ideal sunsail which did not undergo abrasive wear from meteorites should be as light as possible, should be well folded up before launching, and easily unfolded in space.

Tsander showed that a "sail" made of thin plates with thickness of thousandths of a millimeter collected from the thinnest wire (this would be sufficient to preserve the given shape of the mirror surface in outer space outside intensive fields of gravity) with area of 1 km$^2$, may be able to yield a thrust of $p \approx 0.75$ kg, i.e., pressure of $p \approx 7.5 \cdot 10^{-8}$ g/cm$^2$ for a mass of 3000 kg.

Let us call $m$ the total mass of the space sailship, which is the sum of the mass of the sail $m_s = \rho_s \Phi_1$ (where $\rho_s$ is the mass of the sail per single unit of its total surface $\Phi_1$) and the remaining mass of the apparatus $m_0$. Then $m = m_0 + \rho_S \Phi_1$.

The pressure of solar light per unit surface of the sail near orbit around the Earth will be called $p$, and the acceleration obtained will be called $a$. It then follows from the condition of equilibrium of forces acting on the space sailship that

$$a(m_0 + \rho_S \Phi_1) = p\Phi_1 \qquad (2.10)$$

or

$$a = \frac{p\Phi_1}{m_0 + \rho_S \Phi_1}. \qquad (2.11)$$

Substituting the values F. Tsander used for a mirror, i.e., $p = 7.5 \cdot 10^{-8}$ g/cm$^2$ and $\rho_S = 3 \cdot 10^{-4}$ g·sec$^2$/cm$^3$, and disregarding the $m_0$, we find the following approximation:

$$a = \frac{7.5 \cdot 10^{-8} \cdot 1}{3 \cdot 10^{-4} \cdot 1} = 2.2 \cdot 10^{-4} \text{ cm/sec}^2$$

It is easy to find that, for a definite constant specific weight of the sail $\rho_S$, an increase in its area does not bring about an increase of the acceleration over what is determined as equilibrium: /135

$$a = \frac{p}{\rho_S}.$$

In the case under investigation, it would take around 1 month for a sailship on an Earth satellite at orbital velocity of 7.9 km/sec to acquire the second cosmic velocity of 11.2 km/sec, and roughly 65 days to guarantee the velocity for departure from the solar system. We should mention that the additional weight of the light hoist and the payload greatly decreases the rate of acceleration obtained in our example.

F.A. Tsander anticipated the data of sunsails, which now have become feasible, in his suggestion. It has been reported that durable plastic tapes with thickness of about 25 microns which have $\rho_n$ of $3 \cdot 10^{-4}$ g·sec$^2$/cm$^3$, i.e., that which was used in the preceding calculations, have already been produced.

The aircraft then using the sunsail should be put on orbit with the aid of thermochemical or other "thermal" rocket engines.

After going onto orbit, the thrust of the sail is completely sufficient to carry out the requisite maneuvers in space, although at a very slow tempo.

An illustration of a method of bringing an aircraft with sun-sail out of the sphere of gravitation of the planet is represented in Figure 35. We should mention that the Sun itself can aid in unfolding the sail let out on the hoist.

As the technique of obtaining light and reflecting films is perfected, the possibility of using sails for moving small automatic laboratories in the solar system will probably increase. There has already been a design of one such solar yacht which has been published; it is a laboratory with sail of 70 m diameter, weighing 10 kg on the earth, with payload of 10 kg, which is intended for traveling on orbit around Venus and back to the Earth.

The laboratory should gain the second cosmic velocity, passing through numerous loops of a winding spiral surrounding the Earth. In this case, in moving against the pressure of the solar rays, its sail should be removed (or turned edgewise toward the Sun). Becoming a satellite of the Sun, the laboratory gradually deceler- /136
ates with the aid of the sail, and the velocity decreases. As a result, it "falls" on the Sun in a manner similar to the way a satellite descends on the Earth in deceleration, and it goes into orbit around Venus. A further deceleration allows the laboratory to become a satellite of Venus. After scientific research, the laboratory, moving along a spiral around Venus, again gains velocity and floats away, still unfolded, toward orbit around the Earth.

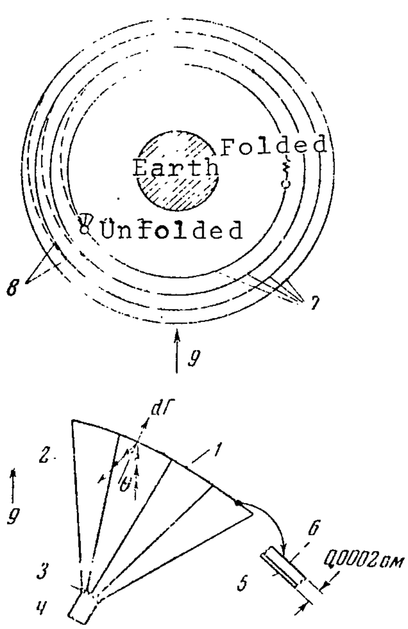


Fig. 35. Withdrawal of a Sunsail from the Sphere of Gravitation of the Planet (the Unfolded Sail, Thrust Vector and Section of the Material of the Sail are Shows Below). (1) Sail; (2) Control Hoist; (3) Apparatus for Winding Hoist and Tilting Sail; (4) Container with Research Equipment; (5) Aluminized Surface; (6) Plastic; (7) Successive Orbit; (8) Trajectories Transferring into a Segment Where Thrust Has Effect; (9) Direction of Solar Radiation.

For a flight on an outer orbit relative to the Earth, e.g., to an orbit around Mars, the solar sailship, becoming a satellite of the Sun, should then gain additional velocity and withdraw from it. If the highest pressure of solar light per unit surface on orbit around the Earth $r_E$ is called $p_E$, then we have the following for an arbitrary distance from the Sun:

$$p = p_E\left(\frac{r_E}{r}\right). \qquad (2.12)$$

As the sailship withdraws from the Sun, the thrust diminishes more and more. The thrust of the sail on orbit around Mars is less than half of the thrust on orbit around the Earth. It is true that, in this case, the solar attraction also decreases in inverse proportion to the increase in distance, but the possibilities of a maneuver, particularly after going into the sphere of gravitation of Mars, nevertheless greatly decrease. /137

The reflectivity of the solar sail worsens in time, in connection with erosion by meteorites and the possibility of a rather rapid disintegration of the plastic by the effect of cosmic radiation. Under the conditions of cosmic vacuum, the plastic can also be sublimated. If these disadvantages can be overcome, the solar sailship may be used.

The sail is capable of maintaining the motion of satellites of a special shape, and it can also guarantee movement of small automatic laboratories within the boundaries of the solar system. Finally, sails can be used for acceleration when the principal engines are out of order. However, all this is possible only within the boundaries of the planetary system. Actually, for acceleration up to a velocity equal to 1/3 the speed of light, which is necessary for a "minimal" interstellar voyage, only one of Tsander's mirrors would be necessary for more than 3000 years at the constant greatest possible thrust!

It is obvious that it is not a realistic task to use the light of heated celestial bodies for spacecraft or sailships, since they should fly at great distances from them.

# 3.

# IN THE DEPTHS OF THE GALAXY

## Again in Search of an Engine

In stellar voyages, spacecraft will go beyond the boundaries of the solar system and will reach other stellar worlds of the Galaxy. We will call the craft which are capable of such voyages galactic craft. /138

The problem of reaching planets of other stellar systems is extremely complex. Meanwhile, a more penetrating study of this problem leads to extreme difficulties. Thus the pessimism of a number of scientists who are examining the problems of interstellar astronautics. As for flights to other galaxies or intergalactic flights, this problem is completely super-fantastic.

However, the distances between the majority of the stars are many orders greater than their size, while the distances between galaxies are commensurate with their sizes. Therefore, as intra-galactic voyages gradually develop then, naturally, in the very distant future, the stage of intergalactic voyages may also be approached.

It is also important to mention that the search for intelligent civilizations in a single galaxy is difficult. It is difficult to judge in which direction, or around which one of numerous similar stars, we should look for an inhabited planet or attempt to capture signals.

Perhaps the search for intergalactic signals will prove to be more successful than for intragalactic ones, since the direction /139 to the neighboring galaxy will be more definite. If there were a civilization in a neighboring galaxy which was capable of sending us signals with power tens of millions of times greater than the energy reserves still used on the Earth, these signals could be received. This power is not too fantastic, considering the rate of development of power engineering on the Earth.

The intergalactic signals could encompass a wide range of frequencies and distances. A search for them would require extensive and systematic studies.

However, the problem of moving material objects in the universe should probably still be limited to distances of "only" several tens of light years. This limitation is imposed so that the problems and the methods of solving it might lend themselves to a technical evaluation on the level of our knowledge and information. Obviously, this approach will aid to an extent in approximating technical evaluations of the difficulties and possibilities of constructing intragalactic craft.

In evaluating the prospects of using an engine for voyages beyond the boundaries of the solar system, in the Galaxy, we should first clarify two basic problems.

First of all, we must know whether or not this engine will impart a velocity comparable to the speed of light when there is an intelligent ratio between the initial and final masses of the craft. As follows from the formula of K.E. Tsiolkovskiy, the exhaust velocity of the working fluid can be no more than one order less than the speed of light for this; in other words, it should be at least tens of thousands of kilometers per second.

Secondly, using this engine, can the great power requirements of the apparatus be guaranteed with the mass ratio obtained, considering the value for the final mass?

It was shown earlier that the liquid propellant rocket engine and the so-called thermonuclear engine are not suitable for flights beyond the boundaries of the solar system, because of the relatively low exhaust velocity of the working fluid.

A computed estimate carried out for an ion engine intended for a stellar course of least distance, to Proxima Centauri, showed that if the exhaust velocity of the working fluid reaches around /140
22% of the speed of light[1], the flight can be accomplished for a ratio between the final returning mass and the initial mass no greater than $1.6 \cdot 10^{-3}$. This means that, if we take the mass of the cabin of the craft with the crew, rations and equipment, engine and power plant as about 200 tons, then the mass of the entire craft during launching from an orbital station with a supply of working fluid brought to the site where the craft was assembled, should be aroung 125 thousand tons. In this case, the two-way flight takes 58 years for acceleration of $a$ = 0.2 m/sec$^2$.

This great weight of an ion craft, which can solve only the simplest problem -- travelling to Proxima Centauri on the condition that a very high (perhaps unachievable) velocity of the working fluid

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1 These high exhause velocities of "heavy" ions in the quantity necessary for producing the thrust are still irrational and unfeasible. They were taken only for a fundamental evaluation of the possibilities of an ion engine.

is obtained -- indicates that the ion apparatus is not too promising for stellar flights.

If we evaluate the mass of the electric power plant for this ion engine, then the problem proves to be completely unrealistic. An acceleration of 0.2 m/sec$^2$, which restricts the flight to 58 years, requires engine thrusts of 12-25 million newtons, i.e., about 1-2 thousand tons, for such great masses of the ion craft (even considering the decrease in mass when firing different stages). In this case, the power of the electric station, calculated according to (2.9), is equal to 800 thousands million kW, which is absolutely fantastic. When the mass of the craft is 200 tons, the specific weight of the station must be on the order of $10^{-6}$ Kg/kW.

For the quantum rocket, when the exhaust velocity is equal to the speed of light, the mass ratio would be 100 times less for the same flight duration, i.e., the requisite thrusts and powers would be less, or, for the same mass ratio we could reach velocities of 0.96 $c$, i.e., three times greater than for the ion rocket.

Finally, we should mention again that, even if the potentials of the ion craft are somewhat expanded by using particles of the intrastellar gas as an additional working fluid, it could not be used for stellar flights because of the unbalance in the weight of the power unit by 6 orders. Therefore, in designing intergalactic and intragalactic craft, we should probably concentrate our efforts on designing quantum craft. Here also, great difficulties in pro- /141
viding the power requirements are unavoidable; however, a decrease in the mass and, consequently, the necessary thrusts (by a factor of 100) has more effect on a decrease in requisite power than an increase in the exhaust velocity to the speed of light (by a factor of 5). Moreover, the use of annihilation reactions does not require special power plants and electric converters, since the energy can be included in the working fluid itself. In this case, we can obtain specific weights of the requisite order. (Let us remember, for example, that they are also low for liquid propellant rocket engines and can be around $1.4 \cdot 10^{-4}$ kg/kW.)

The specific thrusts which can be obtained when using certain types of engines[2], which means their exhaust velocities, are represented in Figure 36. Let us remember that the specific thrust is roughly ten times less than the exhaust velocity. As can be seen, the problem of designing a stellar craft is basically simplified if the thrust is produced by direct ejection of such an ideal working fluid for galactic craft as electromagnetic radiation.

Installing the source of radiation in the rocket, assembling

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[2] Perel'man, R.G.: Dvigateli Galakticheskikh Korabley (The Engines of Galactic Craft). Akad. Nauk S.S.S.R., 1962.

it into a beam with the aid of a deflector and "ejecting" it through the nozzle, we obtain a reaction force which depends solely on the power of the source. But this is only an idea. What do the calculations show?

The pressure of the electromagnetic flux falling perpendicularly on the surface of the body depends on the density of the electromagnetic energy (energy per unit volume) near the surface. The total impulse, which determined the pressure, is the sum of the impulse of incidence and reflected waves. If the /142 capacity of the electromagnetic wave, the "capacity in the beam", per unit surface of the body is equal to $N$, while the reflection coefficient of the electromagnetic energy is $R$, then the density of energy of the electromagnetic waves near the surface is equal to the light pressure per unit surface:

$$p_{\text{unit}} = \frac{N}{c}(1 + R). \tag{3.1}$$

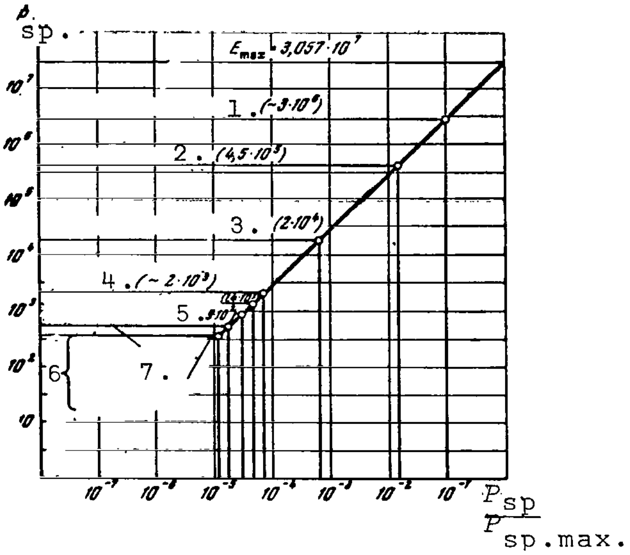


Fig. 36. Specific Thrusts Which Can be Obtained When Using Certain Types of Engines. 1. Thermonuclear Engine 2. Ion Engine, 3. Electroplasma Engine, 4. Atomic Gas Reactor, 5. Electric Ac Engine (Level Attained), 6. Chemical-Drive Rockets, 7. Max. Thearet, Level (Level Attained).

Thus, the light pressure increases with an increase in the reflection factor $R$, which includes from 0 to 1. It is completely clear that the deflector of the craft should reflect the greatest possible amount of energy of the electromagnetic wave incident on it.

What could the electromagnetic emissions scattered by the deflector of the stellar craft be? The electromagnetic waves which are known and have been studied with special instruments span a wide range of wavelengths and frequencies (Fig. 37).

Many of the properties of electromagnetic waves can be explained only by the fact that they are the natural properties of bounded particles, or quanta, or radiation, which have a definite energy and momentum. Both the quantum energy and its momentum are determined by the wave frequency. The longer the wave, the lower its frequency.

Modern physics has shown that a light flux has a discontinuous structure and consists of separate portions (quanta) of light -- photons -- which have definite energy values. Radiation is a continuous process only because of the smallness of the photons and their large number. The photons can be distinguished by their energy characteristics, which depend on the frequency of vibrations. /143

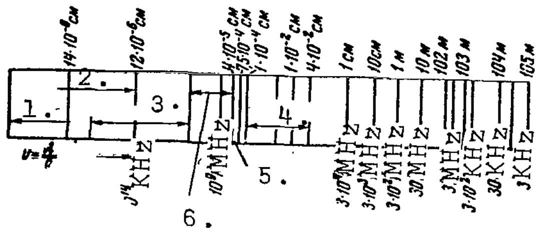


Fig. 37. Spectrum of Electromagnetic Waves. 1. Cosmic, 2. $\gamma$-rays, 3. X-ray, 4. Infrared, 5. Visible Range, 6. Ultraviolet rays.

The impulse of light which is transmitted per unit area of the deflector in a unit time is equal to the following:

$$F = \frac{E}{c}, \qquad (3.2)$$

where $E$ is the emission energy and $c$ is the speed of light.

If the surface absorbs all the quanta, then this impulse also is the pressure of the electromagnetic flux; if the surface reflects some of the quanta carrying the impulse of the opposite direction, it obtains and additional impulse $R \cdot \frac{E}{c}$, and the ion pulse is determined by the same dependence as in (3.1).

To guarantee the thrust and power requirements for a stellar craft, we must find methods for intense and complete nuclear transformation into electromagnetic radiation, avoiding a complex and heavy power plant. These processes can be obtained by analyzing a number of new and fundamentally possible trends.

One of them is to use the phenomenon which occurs when particles collide with antiparticles. The antiparticle is that fundamental particle of a substance which is opposite in charge to an ordinary particle of the same mass. For example, the electron has a negative charge, while its antiparticle, or the positron, has a positive charge. The neutron has no charge whatsoever, but we have found an "inside out" particle for it also -- the antineutron, which has the opposite direction of rotation. The matter which consists of antiparticles is called antimatter.

In our world, antiparticles are short-lived: colliding with ordinary particles and passing through a chain of reactions, they are annihilated, and completely "disappear", with the release of the entire mass and energy in the form of gamma-particles, photons, mesons and other radiation. For example, during annihilation a proton and antiproton are formed, in addition to $\gamma$ - quanta (electromagnetic radiation), and other particles, for example, $\pi^{\pm}$ - mesons. These mesons are divided in a time of $2.5 \cdot 10^{-8}$ sec into $\mu^{\pm}$ - mesons and a neutrino, and then the mesons are divided into $\beta^{\pm}$ - emission (positrons and electrons) and two neutrinos in $2.10^{-6}$ sec. The mesons pass an average distance on the order of hundreds of meters, or kilometers, in this time. Other particles formed in different variations of annihilation pass through roughly the same distances until the moment they are completely converted into electromagnetic radiation.

During annihilation, energy corresponding to the emission of the rest mass of the substance or part of it is released over a unit of the mass taking part in the physical reaction: $E = M \cdot c^2$. Perhaps, other effective methods will be found to obtain a substantial amount of energy confined in the rest mass of a substance.

However, we have still not succeeded in realizing such processes on any substantial scale. For the quantum craft, it would be necessary to produce on the Earth powerful sources, or instruments, to obtain antiparticles, and to put a large reserve of them on board the quantum craft. Let us remember that only a reserve of antimatter, representing a very capacitive accumulator can solve the problem of power.

It can be assumed that, if we could produce anti-iron, for example, then we could preserve it by confining it "by weight" under vacuum far from the walls of the tank with the aid of a constant magnetic field. There is also a basic possibility of confining nonmagnetic charged bodies in a constant magnetic field and of concentrating them with the aid of the same field into a narrow beam during ejection.

The vacuum should be very high. And that density of matter /145 which exists in the space around the Earth can cause local annihilation and overheating of animatter. Its evaporation and explosion follows when it makes contact with the walls.

The Soviet physicist A. Dmitriyev suggested that "magnetic bottles" could possibly be used to preserve antimatter - positrons. This "bottle" is a system of magnetic fields produced by the circulation of strong currents over clothed coils made of superconducting alloys which guarantee resistance of the "walls" without additional energy feeding of the coils. The "bottles" can be distributed alternately in staggered order to balance the interaction of charges if possible. It is suggested that equilibrium be fixed with the aid of electrostatic fields.

The energy of the magnetic and electric fields of the "bottles" as they are vacuumed, as well as the material of the coils, also can be used to provide the energy requirements for the craft.

We should keep in mind that, in attempting to carry out annihilation between any dense stream of antimatter, the reaction, beginning on the adjacent surfaces, would bring about instantaneous dispersion of the remaining part of the "fuel" and its consumption would be negligible. This means that the antimatter should be fed in a very rarified state. As calculations show, their density should not exceed $10^{-10}$g/cm$^3$.

The radiation arising during annihilation would have a harmful effect on the crew and instruments of the spacecraft.

It is shown below that, in the future, it will apparently be possible to produce those combined shields and that conversion of electromagnetic radiation which will eliminate the inadmissible action of radiation on the crew and structures of the craft. At the same time, the shield-deflectors guarantee the direction of a powerful electromagnetic beam producing the thrust opposite to the direction of the movement of the craft.

## Speed and Time for Interstellar Voyages /146

Let us evaluate the velocities and times necessary for completing an interstellar voyage and then the fuel reserves which the prospectors of the Universe may need. We will also attempt to predict the methods used to provide the energy requirements for the spacecraft.

As we already mentioned, an insignificant value of the absolute thrust for spacecraft, compared to their mass (weight) will be characteristic in the foreseeable future. However, it is clear that, the lower the thrust, the more slowly the spacecraft is boosted and the time which will be wasted in the voyage may become extreme. On the other hand, the highest value for the thrust is limited by the fact that the necessary fuel requirements become extremely high.

Let us assume that the acceleration is 0.2 m/sec$^2$, for which the engine thrust in newtons should be roughly 1/5 the intrinsic weight of the spacecraft. It is stipulated that the boosting lasts up to half of the course with subsequent deceleration in the second half, which means that the engine operates continuously (Fig. 38, trajectory 1-1'). In this case, an uncomplicated estimate of the flight time is possible, for example, for Proxima Centauri, with return into the solar system.

The distance spanned in uniformly accelerated motion in

$$L = \frac{at_a^2}{2}\ \text{м}, \qquad (3.3)$$

where $a$ is the acceleration, m/sec$^2$; $t_a$ is the time, sec.

Thus, the flight time, with boosting half the way to the target is

$$t_a = \sqrt{\frac{2L}{a}}. \qquad (3.4)$$

The distance to Proxima Centauri is 4.24 light years. Half of this distance (up to $A$) is equal to $2\cdot10^{13}$km (20 trillion km). With boosting, the flight time is then the following:

$$t_a = \sqrt{\frac{2 \cdot 2 \cdot 10^{16}}{0.2}} = 4.47 \cdot 10^8 \text{ sec} = 14.2 \text{ years} .$$

The subsequent deceleration of the rocket up to entry into the /147
system of Proxima takes the same time. The entire one-way trip takes roughly 28.4 years, and the round trip takes 56.8 years. Up to the end of acceleration, the highest velocity is the following:

$$v_K = at_a = 0.2 \cdot 4.47 \cdot 10^8 = 9 \cdot 10^4 \text{ km/sec}.$$

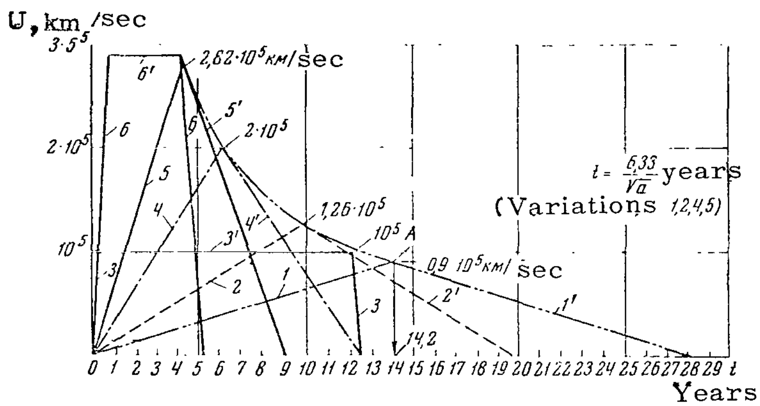


Fig. 38. Some Flight Patterns to Proxima Centauri. (1-1') Flight Pattern for "minimal" Space Craft at $a$ = 0.2m/sec$^2$; (2-2') $a$ = 0.4 m/sec$^2$ with constantly operating engines; (3-3'-3) $a = g_E$ = 9.81 m/sec$^2$ up to $v_K$ = 10$^5$ km/sec with subsequent stopping of the engine and a new connection for deceleration; (4-4') $a$ = 1 m/sec$^2$ with constantly operating engines; (5-5') $a$ = 2 m/sec$^2$ with constantly operating engines; (6-6'-6) $a = g_E$ = 9.81 m/sec$^2$ up to $v_K$ = 2.9·10$^5$ km/sec, stopping the engine and starting anew for deceleration.

The time for an interstellar voyage is determined in the same way, if we assume there are a number of other constant accelerations: $a$ = 0.4 m/sec$^2$, $a$ = 1 m/sec$^2$, $a$ = 2 m/sec$^2$ (see Fig. 38, trajectories 2-2', 4-4' and 5-5'). The results of these calculations are given in Table 4.

Let us further assume that the constant acceleration is equal to that of the Earth and is 9.81 m/sec$^3$. The rocket is boosted with this acceleration up to 10$^5$ m/sec (Fig. 38, trajectory 3-3'-3). Then it travels part of the way with engine turned off (segment 3'), and again it is turned on for deceleration before entry into the planetary system of Proxima Centauri. It is easy to find that a one-way flight takes 12.4 + 0.64 = 13 years, while the entire voyage requires 26 years. The trajectory 6-6'-6 corresponds to flight at the same acceleration and boosting up to 2.9·10$^5$ km/sec.

TABLE 4. DETERMINING THE CHARACTERISTICS OF SPACECRAFT WHICH CAN FLY TO PROXIMA CENTAURI /148

| Nature of Engine Operation | Trajectory on Fig. 38 | Acceleration, m/sec2 | Highest Permissible Velocity $v_k$, km/sec | Travel Time for Crew, Years | Requisite Reserve of Rest Mass per 100 m of Takeoff Mass, m | $\frac{M_0 - M_T}{M_0}$ |
|---|---|---|---|---|---|---|
| Engine operates continuously | 1—1′ | 0.2 | $0.9\cdot10^5$ | 56.8 | 20 | 0.8 |
| | 2—2′ | 0.4 | $1.26\cdot10^5$ | 40.0 | 23 | 0.77 |
| | 4—4′ | 1.0 | $2\cdot10^5$ | 25.3 | 48 | 0.52 |
| | 5—5′ | 2.0 | $2.82\cdot10^5$ | 18.2 | 83 | 0.16 |
| Engine operates part of the time | 3—3′—3 | 9.81 | $10^5$ | 26.1 | 10.5 | 0.77 |
| | 6—6′—6 | 9.81 | $2.9\cdot10^5$ | 10.6 | 99.2 ($\eta$=0.52) | 0.008 |
| | | | | | 93.8 ($\eta$=0.55) | 0.062 |
| | | | | | 86.0 ($\eta$=0.6) | 0.14 |

However, since the flight speed in this case is close to the speed of light, in evaluating the travel time the terrestrial observer must take account of the change in couse of time on the Earth compared to the time spent in the rocket. /149

To determine the least possible duration of a voyage, we must evaluate the highest velocity which can be attained by a galactic craft. The acceleration and deceleration on the way to another world and again the acceleration and deceleration on the way back are unavoidable elements in the trajectory. Let us also remember that the limit speed of light can be obtained only in that case when the entire mass of the spacecraft is converted into electromagnetic radiation, into quanta.

When acceleration up to the speed of light and virtually complete deceleration occur twice, four complete rest masses (natural masses) of the spacecraft would be needed. The unsolvability of this problem is obvious. To what extent can the velocity of a quantum craft approach the speed of light? To answer this question, let us use the generalized equation[3] of K.E. Tsiolkovskiy, which can be used when the apparatus moves at a velocity on the order of the speed of light, i.e.,

$$\frac{M_{\text{к}}}{M_0} = \left(\frac{1 - \frac{v_{\text{к}}}{c}}{1 + \frac{v_{\text{к}}}{c}}\right)^{\frac{c}{2v_{\text{w.f.}}}} \qquad (3.5)$$

[3] In this particular case when the flight speed and exhaust velocity are much less than the speed of light, it is easy to obtain the formula of K.E. Tsiolkovskiy for flights at relatively low velocities.

where $v_k$ is the final velocity of the rocket (velocity at the given moment); $v_{w.f.}$ is the exhaust velocity of the working fluid (for an electromagnetic rocket at $v_{w.f.} = c$, the power of the expression in the parentheses is equal to 1/2).

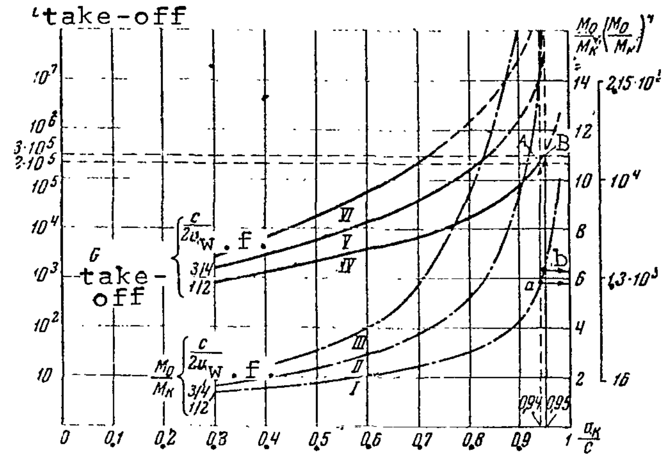


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Fig. 39. Dependence of the Mass Ratio $\frac{M_0}{M_k}$ for a Four-stage Galactic Craft and Its Takeoff "Ground" Weight (for returning weight of 200 m) on the Highest Relative Velocity $\frac{v_k}{c}$. The Dependences Were Obtained for a Number of Exhaust Velocities (Parameter $\frac{c}{2v_{w.f.}}$) in a "Ballasted" Annihilation Reaction.

Expressions $\frac{v_k}{c}$ from (3.5) at $v_{w.f.}$, we find the following:

$$\frac{v_K}{c} = \frac{1-\left(\frac{M_K}{M_0}\right)^2}{1+\left(\frac{M_K}{M_0}\right)^2}. \tag{3.6}$$

It can be seen that, for motion at the speed of light, it is necessary that $\frac{M_k}{M_0} = 0$, i.e., total emission of the rest mass of the spacecraft is necessary.

Assuming that $c = v_{w.f.}$ and substituting into (3.5) a number of mass ratios $\frac{M_k}{M_0}$ corresponding to the case of a single gain in velocity during uniformly accelerated motion, we can find the /151
highest permissible velocity $v_k$ corresponding to each one (Fig. 39, Curve I). Since four stages of acceleration-deceleration predominate for the entire spacecraft, we must quadruple the mass ratio

obtained, i.e., determine $\frac{M_k}{M_0}^4$ which also corresponds to the mass ratio of the craft from the moment of takeoff from the solar system to the moment of re-entry into it.

In the case under investigation, to reach the velocity $v_k$ corresponding to 0.94% the speed of light, the mass ratio marked off by the point $a$ must be guaranteed at each stage, i.e., $\frac{M_k}{M_0} \approx \frac{1}{6}$. Agreeing that this mass ratio (close to the mass ratio for single-stage chemical rockets) can also be guaranteed in one stage of the galactic craft, we can conclude that the rocket should consist of four stages. The cargo, food, equipment, and crew must be put in the forward section. The total mass ratio for it has been only $(\frac{1}{6})^4 = \frac{1}{1300}$.

Similar calculations can also be carried out for those cases when a flux of particles, for example mesons, is formed during the annihilation reaction, in addition to the radiation quanta, and the average velocity of the focused beam is less than the speed of light (the values of the parameter $\frac{c}{2v_{w.f.}} > \frac{1}{2}$ and equal to $\frac{3}{4}$ and 1 for Curves II and III in Fig. 39). As can be seen from the figure, the decrease in exhaust velocity of the particles of the reaction beam brings about the need for a substantial increase in the mass ratio to reach the same velocity $v_k$.

Figure 39 also shows Curves IV - VI which depict the dependence of the take off weight (mass) of a four-stage galactic craft on that value of $\frac{v_k}{c}$ which should be obtained. These curves were calculated on the assumption that, during re-entry into the solar system, the last stage of the space craft with the crew, emergency supplies, and remaining equipment has a ground weight of 200 tons. As can be seen from the graph, even at $v_{w.f.} = c$ (point $A$), the weight of the space craft should be around 210 thousand tons during takeoff in order to reach 94% of the speed of light, and to reach 95% the speed of light (point $B$), 300 thousand tons! That is why /152 the maximum velocity of the space craft will hardly exceed 0.9 - 0.94% the speed of light in the technologically forseeable future.

## Power Demands of Galactic Craft

What are the actual power demands of space craft and the methods which would allow us to provide them?

Let us assume that a space craft has take off mas of $M_0 = 1000$ tons $= 10^6$kg.

We will assume that the constant acceleration of the apparatus is $a = 0.2\ \mathrm{m/sec}^2$. We will also assume, in a preliminary evaluation, that the supplementary increase in velocity due to the decrease in mass of the apparatus connected with its expenditure during the acceleration does not occur or relates to the reserve of calculations.

The takeoff thrust, which is proportional to the mass and acceleration, is then $P = 2 \cdot 10^5$ newtons, which corresponds in the technical system of units roughly $2 \cdot 10^4$ kg, or 20 tons. If we assume that the engine operated, producing this thrust, during the entire voyage to Proxima Centauri and back, then the total energy consumption is the following:

$$E_\Sigma = P \cdot 2L = 2 \cdot 10^5 \cdot 2 \cdot 4.05 \cdot 10^{16} = 16.1 \cdot 10^{21}\ J = 16.1 \cdot 10^{18}\ \mathrm{kW \cdot sec} = 4.5 \cdot 10^{15}\ \mathrm{kW \cdot hr}.$$

where $L = 4.24$ light years $\approx 4.05 \cdot 10^{16}$m is the distance to Proxima Centauri.

The power potentials of all the chemical fuels of the Earth minerals are estimated as roughly $23.5 \cdot 10^{15}$ kW·hr. Consequently, the computed amount of energy necessary for the flight of a 1,000-ton craft is more than 1/5 of all the power reserve of chemical fuel on the Earth.

The mass of a chemical fuel -- a mixture of alcohol and oxygen (1 kg of such a mixture yields roughly $2 \cdot 10^3$ Kcal, or around 2 kW·hr during combustion) would prove to be a billion times greater than the take off weight of the craft for efficiency of the energy source of $\eta = 0.5$. Consequently, it cannot be taken directly on board. For the same efficiency, the requisite mass of the nuclear fuel /153
$U^{235}$ would exceed the takeoff mass of the craft by a factor of 400. It is clear that a nuclear fuel on board a craft also does not provide for the power demands of a spacecraft.

Let us evaluate the possibility of guaranteeing the requirements for a spacecraft by using the energy obtained during a thermonuclear reaction as a result of the synthesis of light elements, when two light nuclei merge into one heavier nucleus.

During the process of the conversion of hydrogen into helium $4H^1 = He^4 + 2e^+$, which is very difficult to realize, it is fundamentally possible to obtain eight times more energy from a unit weight of the raw material than from a unit weight of the nuclear fuel $U^{235}$. However, even in this case the requisite mass of the fuel exceeds the initial mass of the craft almost by a factor of 50. Consequently, this "fuel" must be rejected.

Finally, let us tuen to the possibilities of using the suggested reaction, during which the rest mass of the substance is completely radiated. We will assume that this most complex problem has been solved. The total energy capacity of a kilogram of the substance is then equal to $E = mc^2 = 1\ (3\cdot10^8)^2 = 9\cdot10^{16}$ J. This corresponds to $2.5\cdot10^{10}$ kW·hr/kg, or $2.15\cdot10^{13}$Kcal/kg. As can be seen, the energy capacity of the rest mass is $10^{10}$ times greater than for the most high-grade chemical mixture. In the latter case, we must find the precise consumption of rest mass, with a consideration of the decrease in mass of the apparatus as the "fuel" is processed and the intermediate stages are fired.

Substituting into the generalized equation of Tsiolkovskiy the maximum velocity which is obtained for acceleration of 0.2 m/sec$^2$ in a time necessary for spanning half the distance at the end of the first acceleration segment, we find the following at $v_{\text{w.f.}} = c$:

$$\frac{M_\text{к}}{M_0} = \left(\frac{1 - \frac{0.9\cdot10^5}{3\cdot10^5}}{1 + \frac{0.9\cdot10^5}{3\cdot10^5}}\right)^{1/2} = 0.733.$$

We will agree that the acceleration is constant during the flight time and changes sign only four times (see Figure 38, trajectory 1-1'). The rocket is accelerated twice and decelerated twice. For the entire two-way flight, /154

$$\left(\frac{M_\text{к}}{M_0}\right)^4 = 0.733^4 \approx 0.29.$$

The thrust is connected with the mass and acceleration by the following simple relationship:

$$P = M(t)\frac{dv}{dt}.$$

Since we assumed that $\frac{dv}{dt} = a$ = const, and the mass of the apparatus changes linearly in time, then the thrust should also change linearly, i.e.,

$$P = M_0 - kt, \tag{3.7}$$

where $k = \frac{M_0 - M'}{t}$ ($M'$ is the mass of the apparatus at the end of the segment for which the average thrust is determined).

The average thrust for determining the "fuel" reserves in a segment is equal to the following:

$$P_{\text{av.}} = \frac{P_0 + P_\text{к}}{2}, \tag{3.8}$$

where $P_0$ and $P_k$ are the initial and final values of the thrust.

Then, for example in segment 1 (see Figure 38), i.e., in the acceleration, the requisite energy consumption per 1000 tons of take-off mass is equal to around $0.81 \cdot 10^{15}$ kW·hr, or $0.8 \cdot 10^{18}$ Kcal, and the requisite reserve of rest mass in this segment is

$$M = \frac{E_{0-1}}{\eta E_{unit}} = \frac{0.81 \cdot 10^{18}}{0.5 \cdot 2.15 \cdot 10^{13}} = 78{,}000 \text{ Kg}.$$

The expenditures of the rest mass are calculated for the remaining segments of the trajectory with a consideration of the decrease in $P_{av}$. The total requisite amount of rest mass is 205 tons for efficiency of $\eta_{tw} = 0.5$ on the trajectory 1-1'.

Thus, the reserve of rest mass necessary to guarantee the power demands of the "minimal" space craft in using the entire reserve of intrinsic energy of the substance with efficiency of $\eta_{tw} = 0.5$ is admissible. If we assume that it is not impossible to have even a partial gain of the "fuel", or the mass expended, on the planet reached for the return trip, then the solution to the problem is made easier. The expenditures of rest mass for boosts with /155 the other accelerations and trajectories shown in Figure 38, which correspond both to cases when the engine operates constantly and to cases when, after acceleration to a certain velocity, the craft covers part of the distance with its engine shut off, and then the engine is shut off for deceleration, are calculated in a similar manner.

Thus, in order to guarantee power for the space craft, we must penetrate into the innermost depths of matter and master processes to obtain energy due to the emission of the rest mass of a substance. Only by penetrating into the secrets of the microworld will we find the way to other stellar worlds and galaxies.

## In the Interstellar Medium

For the galactic craft, the interplanetary space, which is pierced with fluxes of strongly ionized gas consisting of electrons and protons ejected from the surface of a star, and "contaminated" by meteor particles, is a substantial obstacle in the way to interstellar space, both for takeoff from any stellar system and for return to it. The overcoming of this obstacle is made somewhat simpler in that the segments of the course around the stars are relatively small, and thus the craft passing through them only begins to be accelerated or decelerated. For example, its velocity obviously does not exceed $10^4$ km/sec up to the boundaries of the solar system. Finally, we can assume that the galactic craft should take off from the outer most planet of stellar systems.

Doubtless fundamental and unknown dangers, the uniqueness of which is now difficult to project, await galactic craft in the interstellar space itself. Let us evaluate the difficulties in a flight in the interstellar medium and find at the same time whether or not it is possible to use interstellar matter in order to supply the craft with the rest mass corresponding to its power demands. In our approximating examination, we will not take account of the eigen-velocity of the interstellar gas, which can be very low compared to the velocity of the apparatus. Moreover, we will limit /156 ourselves to an investigation of the eigen-velocities of the apparatus which are only of 1 order with the speed of light.

The space which stellar craft should pass through is filled with real matter -- the interstellar medium, as well as electromagentic emissions and fields of gravity. Of the entire mass of our Galaxy, which is roughly $26 \cdot 10^{38}$ tons, a substantial amount is interstellar gas, dust, etc. The stars seem to be immersed in a fog of gas and fine dust particles which are on the order of a ten-thousandth of a millimeter in size, a distance of tens of meters away from each other.

The average density of the interstellar matter beyond the boundaries of planetary systems, if it were distributed uniformly, would be an insignificant value[4]: $\rho_e = 10^{-23.5 \pm 1}$ g/cm$^3 \approx 10^{-24}$ g/cm$^3$. This corresponds to the existence of from 0.2 to 20 atoms per cm$^3$ of space, or a percentage of from 7 to 70 g of matter in the volume of the moon. Let us remember that there are $2.7 \cdot 10^{19}$ molecules in 1 cm$^3$ of space near the Earth.

The interstellar matter is concentrated in the plane of the Milky Way and is accumulated into clouds of different sizes and of a density which greatly exceeds the average density of the interstellar medium. In nebulae of gas and dust, the concentration of interstellar matter increases by a factor of $10^3$-$10^4$. The dust is intermixed with gas particles which are 100 times greater in mass than the dust. The cosmic dust particles are $10^{-4}$-$10^{-5}$ cm in size. These dust particles absorb light, and therefore make observation of objects which are in the galactic plane at distances exceeding 2-3 thousands of parsecs impossible. Therefore, astronomers can observe objects at distances of hundreds of millions of light years only when the direction of them makes a substantial angle with the galactic plane. Perhaps, in the case of flights to distant stellar worlds, we will have to lay out the route indirectly, "vertically" beyond the boundaries of the layer of gas and dust. The motion would then be parallel to it and the galactic plane, with subsequent entry into the gas-dust layer near the target.

It is considered that about 90% of the interstellar gas is atomic hydrogen, and the remaining amount is sodium, potassium,

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[4] In the physical system of units (CGS).

calcium and others. The physical properties of the interstellar gas depend on what distance it is from hot stars. The ultraviolet radiation of hot distances. I.S. Shklovskiy noted that the star of the 0.5 spectral group ion is the hydrogen around it in a range with radius greater than 100 parsecs. Nevertheless, most of the interstellar matter is so far removed from hot stars that the majority of hydrogen atoms are not ionized. This is important in connection with the problem "purifying" the space in front of the craft from interstellar matter. /157

It was recently established that magnetic fields are connected with the clouds of interstellar gas. The intensity of their lines of force coincide in direction with the spiral arms of the Galaxy, which represents magnetic tubes of force of gigantic dimensions. Particles of cosmic rays move along the lines of force of the interstellar magnetic fields along spiral trajectories. They are protons, nuclei of the heavier elements, and electrons whose energies exceed hundreds of millions of electron volts. Moving in the interstellar magnetic fields, the electrons emit radio waves, which we observe as the radio emission of the Galaxy. The clouds of interstellar matter move at a velocity from several kilometers to tens of kilometers per second. Let us make an approximating estimate of the amount of interstellar matter which can interact with the rocket during its flight, e.g., from the Earth to Proxima Centauri.

We will calculate the mass of interstellar matter $m$ which is included in a column, for which the base is equal to 1 $cm^2$ and the length is the distance between the Earth and Proxima Centauri $L = 4\cdot 10^{18}$ cm. Since the average density of the interstellar medium $\rho \approx 10^{-24}$ $g/cm^3$, we can write the following in first approximation:

$$m = \rho_\varepsilon L \approx 4\cdot 10^{-6}\,\text{g/см}^2. \qquad (3.9)$$

If we attempt to accumulate interstellar matter with the aid of a collector which has input area of $\Phi = 1$ $km^2$, then we could have a mass equal to $m' = m\Phi \approx 4\cdot 10^{-6}\cdot 10^{10} \approx 40$ kg inside the rocket after a flight to Proxima Centauri. This is 5000 times less than the least rest mass of annihilating substances (205 tons) necessary for the flight of a craft with mass of 1000 tons to the closest star. In other words, to guarantee the flight of a spacecraft with such mass, it would be necessary to collect interstellar matter from an area of $5\cdot 10^3$ $km^2$. Obviously, this problem cannot /158 be solved either by a "rigid" collector or certain force fields. Thus, it is impossible to provide the power demands of a spacecraft by collecting and using interstellar matter.

Perhaps the use of masses concentrated in the "tracks of matter" connecting distance galaxies will prove to be more successful in the distant future. The density of the substance in such "tracks" could be 1000 times greater than that in the interstellar medium.

Let us estimate the decelerating effect of interstellar matter on the motion of a rocket flying at velocities around the speed of light. In the case when the velocity of interstellar gas which has natural density in relation to the rocket of $\rho_e$ is equal to $v_g$, the density of this gas is greater than $\rho_e$ for the crew of the rocket. This is natural[5], since, on the one hand, the mass per unit volume of space spanned by the spacecraft is increased for the crew so that

$$\frac{m}{m_e}=\frac{1}{\sqrt{1-\left(\frac{v_g}{c}\right)^2}},$$

and, on the other hand, because of the shortening of the length in the direction of motion, so that

$$\frac{L}{L_e}=\frac{1}{\sqrt{1-\left(\frac{v_g}{c}\right)^2}}.$$

As a result, the density of the surrounding masses is equal to the following for the crew during motion of the rocket:

$$\rho_e'=\frac{mL}{m_eL_e}=\frac{\rho_e}{1-\left(\frac{v_g}{c}\right)^2}. \qquad (3.10)$$

The mass of the gas which is incident on a cross section of the rocket $\Phi$ per eigen-second of its flight is then the following: /159

$$m'_{sec}=\frac{dm'_e}{dt_e}=\frac{\rho_e\Phi v_g}{1-\left(\frac{v_g}{c}\right)^2}. \qquad (3.11)$$

Thus, the decelerating impulse, pertaining to the cross section of the rocket $\Phi$ is equal to

$$P_e=\frac{dI_1}{dt_e}=\frac{dm'_e}{dt_e}v_g=\frac{\rho_e\Phi v_g^2}{1-\left(\frac{v_g}{c}\right)^2}. \qquad (3.12)$$

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[5] The eigen-velocity of the rocket flight $v_e$, considering the relativistic shortening of the distance $v_e = c \arctan \frac{v_g}{c}$ can be greater than unity, since the velocity calculated according to the time spent in the rocket and the distance spanned by the rocket, measured from the Earth, is taken as the eigen-velocity.

This is also the pressure of the masses which impede motion. At $\frac{v_e}{c} \ll 1$, the latter equations convert into the following classic dependences:

$$m_{sec} = \rho_e v \Phi \text{ and } P_e = \rho_e v^2 \Phi. \tag{3.13}$$

The results of calculations according to (3.12), after introducing the natural rocket velocity $v_e$ into it, are given in Figure 40 for a number of values of $\frac{V_e}{C}$.

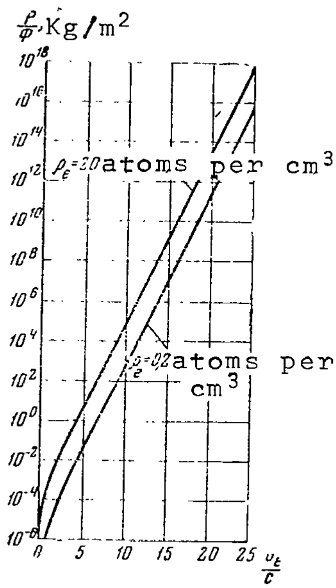


Fig. 40. Deceleration Produced by the Interstellar Matter as a Function of $\frac{v_e}{c}$ for Two Values of its Density.

As can be seen from Figure 40, when $\frac{V_e}{C} \ll 1$, the deceleration of the rocket /160
in the interstellar medium should become substantial. In this case, the only way of compensating for the dray is to take this medium into the rocket and then eject it continuously at the speed of light, with complete converging of the energy of the oncoming mass to radiation. Finally, the acceleration or deceleration in this case can be realized only by using the mass preserved in the rocket.

Let us further discuss the dangers of the craft contacting the interstellar gas, colliding against it. The velocity of even the first galactic craft should be on the order of the speed of light, and this means that the frequency of collisions between the outer walls of the rocket and particles of dust and interstellar gas is close to the frequency at which the bombarding particles penetrate into the nuclei of atoms of the structural materials of the rocket.

Thus, in addition to erosion and eruption of the envelope of the rocket with the smallest dust particles, as well as the unavoidable interaction with atoms of the gas (particularly dangerous for their tangential incidence on the walls) and cosmic dust particles, there is a danger of a change in the properties of the material of the envelope in connection with the bombardment of the nuclei of its atoms. All of these interactions can bring about the erosion of the envelope of the apparatus and the arisal of showers of particles which have a fatal effect on the crew and apparatus.

It is easy to see this after examining Figure 41. The flight speed is plotted along its horizontal axis, in relation to the speed of light. On the first vertical scale on the left, we have plotted the energy of a proton colliding with the envelope of the rocket; on the second scale, we have plotted the energy of protons of the interstellar gas for one year of flight per $m^2$ of the cross section of the rocket (when the density of the interstellar gas $\rho_e = 10^{-24}$ g/cm$^3$).

On the first vertical scale on the right, we have shown the weight coefficient of the amount of trinitrotoluene which should be "exploded" over a square meter of the cross section of the frontal armor of the rocket in order to release as much energy as /161 is released over the same area when the atoms of interstellar hydrogen collide. On the second scale on the right, we have shown sample amounts of potassium carbide which can be evaporated from 1 $m^2$ of the frontal armor of the rocket as a result of collisions with particles of the gas (on the condition that all of its energy is transmitted to the envelope). Thus, the graph allows us to discuss the mass of heat-resistant material which is necessary for shielding the craft.

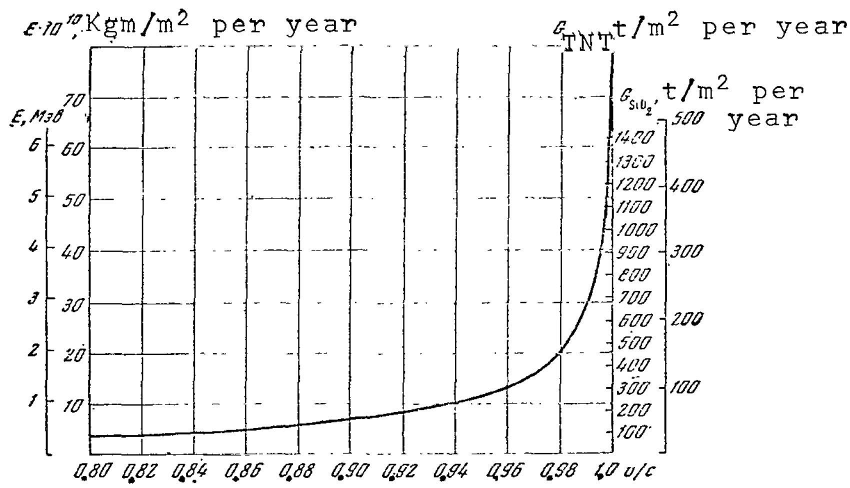


Fig. 41. Energy of Particles Colliding Against a Rocket, and Requisite Masses of the Protective "Armor" of the Rocket as a Function of Its Flight Speed.

The possibilities of shielding a galactic craft from destructive interaction with the interstellar gas are represented in different ways, depending on their velocities: protection for a velocity roughly ten times less than the speed of light, for a velocity of the same order as the speed of light but much less and, finally, for a velocity approaching up to the speed of light.

I.I. Chudakov wrote that protection from radiation is easily feasible when the craft has a velocity of 30 thousand km/sec, i.e., 0.1 $c$. The protons and electrons with such velocity, colliding with the rocket, do not generate penetrating radiation and electromagnetic emission. During an increase in the velocity up to 100 thousand /162 km/sec (close to the highest velocity for the "minimal" spacecraft), the requisite mass of the field increases, but nevertheless remains admissible.

When the velocity reaches roughly 1000 km/sec, nuclear processes occur on the surface of the armor. Roughly 1 thousandth of the colliding mass of gas converges into radiation, and the remaining is used for heating up and destroying the armor.

In order to understand the amount of "armor" which is evaporated by the effect of the particles, we will only mention that one gram of particles colliding with the craft brings about roughly the same effect as 22 thousand tons of TNT.

A rocket should pass through a course of $10^{24}$ cm in order for 1 $cm^2$ of the surface of the "armor" to collide against 1 g of the substance, when its density in space in $10^{-24}$ $g/cm^3$. Since the distance to Proxima Centauri is roughly 250 thousand times less ($h = 4 \cdot 10^{18}$ cm), 1 $cm^2$ of the rocket surface collides over this distance with only four millionths of a gram of interstellar matter, which is equivalent to the effect of 80 kg of TNT. The flight lasts around 10 years ($3 \cdot 10^8$ sec); consequently $2.7 \cdot 10^{-4}$ g of TNT acts on the surface of the rocket every second, i.e., roughly 1 gram of TNT explodes over 1 $cm^2$ in one hour.

It is assumed that, for protection from the action of interstellar gas, in addition to the special shield-deflectors which F. Yasinskiy proposed[6], we could also use multi-layered shields which absorb the energy of an explosion, as well as $\gamma$-rays which are formed during nuclear interactions, and even antiparticles. These shields could be replaced as they are expended.

Let us give one more example showing the fundamental possibility of protecting the envelope of a rocket moving at velocities on the order of the speed of light. A radiator set-up which is of low power compared to the principal engine, the radiator projecting the /163 electromagnetic beam forward, is one more variation of an active shield clearing the way for a galactic craft. For example, using 1/10,000 of the mass of the craft, we can "nullify" the cosmic particles impeding its motion.

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[6] The shield is fixed some distance from the craft and shifted to the side where the meteor fluxes are most intensive. The thickness of the shield is selected in such a way that a dangerous meteorite pierces through it. Than a gaseous bunch is formed behind this shield, and it cools off and is partially scattered in time before reaching the skin of the craft.

Perhaps an electromagnetic shield will also be designed. This shield would appear as a magnetic field especially excited during passage through dangerious zones. It would incline toward impacting charged particles. The particles which do not carry a charge could be preliminarily ionized by radiation directed in front of the movement of the craft, and then also deflected from its path.

We mentioned earlier that bright stars ionized the interstellar gas around it by hundreds of parsecs. Therefore, for certain zones in space, we can count on diverting the gas from the path of the craft with the aid of special magnetic fields, without using energy for its ionization.

In addition to the elementary particles on the path of the craft, there can also be meteorites which are capable of piercing through its armor. When the velocity of the craft increases, it is more and more difficult to carry out even the most insignificant deviation from course in order to avoid collisions; therefore, for a velocity on the order of the speed of light, we must look for methods to annihilate the meteorites, and to "drive off" particles of the interstellar gas from the course or receive them only on the protective seals and armor of the craft.

Naturally, while we attempt to overcome the difficulties connected with the erosion of material of the rocket and change in its properties, we may find new materials and structural solutions.

For a velocity of the craft which approaches all the way to the speed of light, the possibilities of protecting the walls become paradoxical at first glance. Obviously, there is a radiation coming from the armor of the rocket and directed forward in this case when the body of the rocket interacts with the particles of interstellar gas. It also affects new particles flying toward the rocket, and they in turn are converted into radiation. This regime of a particle flux flowing around the rocket occurs when almost the whole mass of the oncoming gas is converted into radiation at a certain distance from it. To maintain the automatic shielding /161
regime, it is sufficient for one millionth of the oncoming particles to be incident on the surface of the rocket.

The surface where the cosmic particles are "revised" into radiation is at a large distance from the spacecraft; therefore, the radiation which reaches the cabin is obviously hundreds of thousands of times less than that during direct interaction between the particles and the walls. A relatively thin lead umbrella-shield in front of the craft is in decreasing the effect of interstellar matter on the walls down to completely tolerable limits.

We have mentioned that, in addition to the regions in which there are clouds with increased concentration of interstellar matter, there are also those where the concentration of interstellar matter is low; these are unique clear paths. The stellar craft should be directed along them.

## The Appearance of the Spacecraft
(On the system forming the thrust path)

The most complicated problems in the field of designing galactic craft are still only beginning to be studied; however, we should now carry out studies which will allow us, in final analysis, to approach a technical solution to the problem.

Since one of the principal units of the craft is the system which guarantees directed reflection of the flux of electromagnetic radiation producing the thrust, let us examine the possibilities of designing this system and its dimensions. We will discuss four types of seals: "optical" fields which reflect the quanta of visible light - photons; "rod-type" fields which reflect electromagnetic waves, or quanta of the radar range; "electromagnetic" seals, formed by electric and magnetic fields of a given form, capable of reflecting all the particles composing the radiation of the energy source of the spacecraft; "plasma" seals.

The coefficient of energy absorption in the material of the seal is equal to the following: /165

$$\varepsilon = \frac{4\pi\Delta}{\lambda}, \qquad (3.14)$$

where $\lambda$ is the length of the electromagnetic wave; $\Delta$ is the depth to which it penetrates into the material.

It follows that, as the wavelength increases, the absorption of its energy in the reflecting field decreases.

Turning to the spectrum of electromagnetic radiation represented in Figure 37, we can see that the very short waves should be particularly "stable" in relation to the material of this field. For example, for $\gamma$-radiation, which can be formed during the collision of particles and antiparticles, even ideally polished optical shields are similar to a sieve. At the same time, a substantial amount of the other particles formed, which means a substantial amount of the emission energy, is absorbed by the material of the optical shield.

Visible light, or photons, is absorbed somewhat less in the shield and is better reflected. However, even the best polished silver mirror absorbs up to 5% of the energy of the light incident on it in this case also ($\varepsilon$ = 0.05). When the wavelengths increase, their absorption descreases. Thus, for a wavelength of 10 cm, the absorption coefficient of its energy in the reflecting shield is around a hundred-thousandth, and it is three times less for a wavelength of 2 *m*.

It was natural to begin the investigation of the possibilities of designing shields in correspondence with Figure 37 "from left to right", i.e., with electromagnetic shields for hard rays. However, the popular-science and science-fiction literature have had a determinant effect on the order of examining them. Actually, in any discussion of the possibilities of designing an interstellar craft, it has recently been called the photon craft, i.e., a craft which discharges visible light. This design, with a super-powerful radiant light flux, brighter than tens of suns, was obviously most effective and corresponded most to ideas to which we are accustomed.

That is apparently why specialists also discussed it first. The first impression was very discomforting. Actually, if 5% of the energy of light incident on the best polished silver field is absorbed in it, the construction of a photon spacecraft is almost impossible. Let us remember that, to obtain a thrust of one ton /166 (around $10^4$ newtons), we must have a radiation source with a power of near 1.66 billion kW[7]. Approximately the power of 2500 power plants, such as Dnyeproges. However, for a flight to the nearest stars, a thrust of tens and hundreds of tons is necessary. Also necessary are very powerful radiation sources directing large currents of radiation. For the emission of 20 billion kW, the field would absorb energy of about 1 billion kW, or 0.24 billion Kcal/sec, which would make the danger of the shield evaporating very acute. To cope with these heat fluxes, the nozzle of the spacecraft should have a huge area of radiators.

As noted by G.I. Babat, the first scientist who attempted to evaluate the dimensions of the "optical" shield of a spacecraft, even if we assume that the concentration of the radiation flux on the shield of the spacecraft is only 10 times greater than that on the surface of the Sun, then the reflectors should have an area of several square kilometers. The technical difficulties in designing an optical shield seemed insurmountable. Thus, we turned to an examination of the "radar", or shield for a galactic craft.

An example of the radio-frequency waves which are directed successfully by shields or deflectors and are absorbed by them to an insignificant degree are radar or television waves. Any radar instruments can be called the prototype of the engine of the craft. It is true that the specific weight of such an engine would be extremely high, since very powerful energy levels are required and the effectiveness of converting other types of energy into radio-frequency waves is extremely low for the sources we know of.

What is very important, the shields or deflectors of the radio-frequency waves can be made, not as one piece, but in the form of

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[7] Correspondingly, in the case when the thrust is generated by "active" emission from the surface of the shield itself, in which the emission is almost not absorbed, to obtain a thrust of one ton we must have an emission source with power of about three billion kW.

a widely-spaced grid, because of the long wavelength in correspondence with (3.14). The engine weight can thus be substantially decreased. This makes the use of radio-frequency waves, of the meter range for example, very attractive for a quantum craft.

The following dependence is used in radar technology to determine the diameter of the antenna (screen): /167

$$D_S = \frac{\lambda}{\varphi_l} \quad (3.15)$$

where $\phi_l$ is the width of the radiation pattern in radians, taken for that change in direction from the axis of the antenna for which the power of the emission decreases by half (the value of $\phi_l$ is usually preset).

For the quantum craft (3.15) can be used only in determining the open angle of the ray. The smaller this angle, the lower the losses in thrust. We will further assume that the open angle of the ray should not exceed 1°.

The absolute value of the power loss in the screen will be determinant in selecting the size of the screen of the spacecraft. Let us estimate this size.

For a mass ratio of the apparatus $\overline{M}$ determined with the aid of (3.5), its takeoff mass should be

$$M_0 = M_{\text{к}}\overline{M}. \quad (3.16)$$

In order to impart to the spacecraft the requisite constant acceleration at the beginning of the 0-1 segment, the engine thrust (first stage) should be

$$P = M_0 a. \quad (3.17)$$

To produce a unit thrust due to electromagentic radiation with an ideally reflecting shield, the power must be distributed thus:

$$N \approx 0.5kPc, \quad (3.18)$$

where $k$ is the coefficient of conversion of the power of the emission source into the thrust $P$.

Calling the coefficient of absorption of the power in the deflector $\xi = 1-R$, where $R$ is the reflection factor, we find the following for the heat release in the deflector:

$$N_S = 0.5kPc\xi. \quad (3.19)$$

The spacecraft is a body which is in radiative heat transfer with the surrounding medium. Agreeing on a permissible temperature of the deflector $T$, and considering the Stefan-Boltzmann law (from the condition that the temperature of the deflector does not exceed a permissible value), we can write the following: /168

$$N_{S} = N\xi = \sigma_0 T^4 \varepsilon \Phi, \tag{3.20}$$

thus, the area of the rods of the deflector is equal to

$$\Phi = \frac{N\xi}{\sigma_0 T^4 \varepsilon}, \tag{3.21}$$

where $\sigma_0$ is the Stefan-Boltzmann constant; $\varepsilon$ is the coefficient of natural radiation of the rods. This radiation is in the infrared spectral range (wavelength of about 10μ). $\Phi$ is the area of the surface of rods composing the screen.

For wavelengths of $\lambda$, the width of the screen mesh may be roughly $h = \lambda/10$. Let us assume that the screen is made of rods (tubes) with a diameter of $d$. The surface of the rod composing one side of the mesh is equal to the following:

$$f = \pi d \cdot \frac{\lambda}{10} \approx 0{,}314\, d\lambda.$$

Considering that the rods emit the "ultra" part of their surface into space and considering the coefficient $k_{sh} = 0.8$ of their reciprocal shading, we can find the total number of rods composing the screen:

$$n_{r} = \frac{2\Phi}{f k_{sh}} = \frac{2\Phi}{0{,}314\, d\lambda \cdot 0{,}8} \approx 8\frac{\Phi}{d\lambda}. \tag{3.22}$$

It is easy to show that the number of meshes $n_m$ of a square screen is connected with the amount of rods forming them by the following equation:

$$n_{r} = 2\sqrt{n_m}(\sqrt{n_m} + 1). \tag{3.23}$$

We can assume in first approximation that $n_m = 0.5\, n_r$ when there is a large number of meshes. Then, for an approximate determination of the number of square meshes of the screen, we find the following dependence:

$$n_m = 0{,}5 n_r = 4\frac{\Phi}{d\lambda}. \tag{3.24}$$

Assuming that the screen is flat and square, and knowing the number of meshes in it, it is easy to write the expression to determine the size of a side of the screen as a function of the radiation wavelength:

$$H = 0.1\lambda \sqrt{n_m} \tag{3.25}$$

or, in turn, /169

$$D_{s.sph.} = 0.8H, \tag{3.26}$$

where $D_{s.sph.}$ is the diameter of the hemisphere of the same area as the square screen (equivalent area of a hemispherical screen $S$).

Substituting all the intermediate values found into the equation determining the diameter of the hemispherical screen, we find the following equation to evaluate $D_{s.sph.}$:

$$D_{s.sph.} = 0.16 \sqrt{\frac{N\xi\lambda}{\sigma_0 T^4 \varepsilon d}} \tag{3.27}$$

considering (3.16)-(3.18):

$$D_{s.sph.} = 0.16 \sqrt{\frac{kM_{\text{к}}\overline{M}ac\xi\lambda}{2\sigma_0 T^4 \varepsilon d}}. \tag{3.28}$$

To determine the diameter of the hemispherical screen of a "minimal" spacecraft, i.e., one which flies at minimal acceleration $a$ = 0.2 m/sec$^2$, as defined above, we must first determine its total requisite thrust. The flight pattern for this case is represented in Figure 38 (trajectory 1-1'). Let us assume that the load which should be returned to the solar system has a mass[8] of 1000 tons. Then, as follows from the calculations made earlier, the mass ratio should be $\overline{M} \approx 3.5$, which means that the minimal mass of the apparatus during takeoff should reach around 3500 tons ($35 \cdot 10^5$ kg).

To impart an acceleration of 0.2 m/sec$^2$ at the beginning of the 0-1 segment, the thrust should be $P = M_0 a = 35 \cdot 10^5 \cdot 0.2 = 7 \cdot 10^5$ newtons, i.e., around 70 tons in the technical unit system.

As we already mentioned, since a power of about three billion kW must be provided to produce one ton of thrust by electromagnetic

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[8] The estimate made is valid for any number of masses 1000 tons each. Basically, this heavy weight of the returning section of the craft was taken in view of the extremely long course and probable intersection of the power unit in the "first" craft.

radiation, with an ideally reflecting screen, the total requisite power should be 210 billion kW, according to (3.18). The heat release in the material of the screen is equal to 210 $\xi$ billion kW. The requisite dimensions of the screen depend on the value of $\xi$, or the loss factor from absorption of the power in the screen. /170

The dimensions of the screen are evaluated for a number of values of $\xi$. Obviously, we must find that value of $\xi$ where the dimensions of the screen remain technologically permissible or, on the other hand, where a high value of $\xi$ (if it cannot be decreased) determines that structure of the screen which allows us to preserve its strength and working capacity.[9]

We will use (3.27) for further calculations, for following values will be used in it: according to the calculations above, $N$ = 210 billion kW = $210 \cdot 10^{12}$ W = $5 \cdot 10^{13}$ cal/sec; $\lambda$ = 200 cm; $\sigma_0$ = $1.36 \cdot 10^{-12}$ cal/cm$^2$ sec$\cdot$deg$^4$; $\varepsilon = 1$; $T$ = 573° K.

When the absolute temperature of the rods composing the screen increases, its heating due to the increase in the absorption factor also increases. In view of this, we also stopped at the permissible temperature of $T$ = 300° C = 573° K. The diameter of the rods was taken preliminarily as equal to 1.3 cm, and for a unit of this length we used an area of ~ 4 cm$^2$. It is necessary to use not rods but tubes of the same diameter to decrease the mass of the structure without substantial effect on the strength of the screen. Let us also remember that the screen is in a state of weightlessness and is strained only by a uniformly distributed load, or thrust of $P$ = 70 tons.

Assuming in the first case that $\xi = 10^{-9}$, and substituting the known values into (3.27), we can find the diameter of the screen as equal to 11.6 m. When $\xi$ increases, the size of the screen increases:

$$D_s = D_{s'} \sqrt{\frac{\xi_s}{\xi_{s'}}}. \qquad (3.29)$$

The results of the corresponding calculations are given in Table 5; the curve for $D = f(\xi)$ is constructed in Figure 42.

Let us turn to an evaluation of the dimensions of screens on the stages of the "maximal" quantum craft, which develops a velocity on the order 94% of the speed of light, corresponding to $\overline{M}$ = 1300, according to (3.5). Let us agree that the mass returning into the solar system is equal to 200 tons, while the thrust and power /171

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[9] As the mass of the spacecraft is processed, to preserve $a$ = const, the thrust should decrease, which means the dimensions of the screen may also be decreased. This problem can be solved, for example, by gradual ejection of the outer annular sections of the screen.

of the engine of the first stage of the spacecraft, to obtain an acceleration of $a$ = 0.2 m/sec$^2$, are equal to $P_0$ = 5.1·10$^7$ newtons (5.2·10$^3$ tons), and $N$ = 15.6·10$^3$ billion kW.

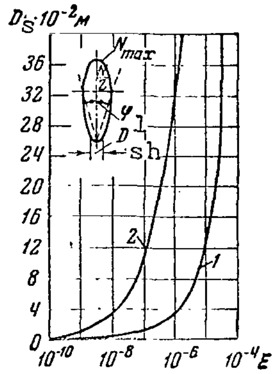


Fig. 42. Example Dependence of the Size of a Rod-Type Screen of the First Stage of a Galactic Craft on the Coefficient Energy Absorption in the Material of the Screen. (1) "Minimal" Spacecraft; (2) "Maximal" Spacecraft (with Proposed Maximal Relative Velocity of $v$ = 94% $c$).

As a result, we find the dimensions (diameter and area of a rod-type screen) represented in Table 5 and Figure 42 for a number of values of $\xi$. As can be seen, the loss factor should be decreased if possible down to $\xi = 10^{-7}$. In our era, there are no screens

TABLE 5. DIMENSIONS OF A ROD-TYPE SCREEN FOR DIFFERENT VALUES OF THE LOSS FACTOR $\xi$

| Loss Factor $\xi$ | "Minimal Spacecraft" | | | "Maximal Spacecraft" | | |
|---|---|---|---|---|---|---|
| | Area m$^2$ | Diameter m | Specific Pressure, g/m$^2$ | Area m$^2$ | Diameter m | Specific Pressure, g/m$^2$ |
| $10^{-9}$ | 210 | 11.6 | 3.33·10$^5$ | 15.6·10$^3$ | 100 | 3.33·10$^5$ |
| $10^{-8}$ | 2.1·10$^3$ | 36.6 | 3.33·10$^4$ | 15.6·10$^1$ | 316 | 3.33·10$^4$ |
| $10^{-7}$ | 2.1·10$^4$ | 116 | 3.33·10$^3$ | 15.6·10$^5$ | 1000 | 3.33·10$^3$ |
| $10^{-6}$ | 2.1·10$^5$ | 366 | 3.33·10$^2$ | 15.6·10$^6$ | 3160 | 3.33·10$^2$ |
| $10^{-5}$ | 2.1·10$^6$ | 1.16·10$^3$ | 33.3 | 15.6·10$^7$ | 10000 | 33.3 |

with such an insignificant absorption factor. The value of $\xi$ for a screen made of copper pipes at $\lambda$ = 2 m is 0.3·10$^{-5}$. If $\xi = 10^{-6}$ and then $\xi = 10^{-7}$ are obtained, this will doubtlessly be because great difficulties have been overcome. This is all the more to since, for screens made of other materials, the absorption coefficient for waves of identical lengths is greater than that for copper (for example, $\xi$ in iron is roughly 2.5 times greater than in copper, for a wavelength of 2 m). It is desirable to increase the diameter of the rods of the screen; this would correspond more to the structural dimensions of the spacecraft and would decrease the initial mass of the screen. /172

The second stage of the spacecraft under investigation has a mass equal to 1/6 of the first, and the area of the grid screen of its engine is 1/6 the area of the screen of the first stage. The diameter of its screen is equal to $D_2 \approx 0.3\sqrt{S_1}$. The screen of the third stage is in the same ratio with the area of the screen of the second stage and, finally, the screen of the last and fourth stage is in the same ratio with that of the third stage. The fourth stage and its screen are close in size to those which are necessary for the "minimal"spacecraft.

To protect the crew of the spacecraft from the emissions of a natural power source, additional deflecting screens placed behind each other will be necessary, even if the crew is at a great distance from it. The screens of the middle stages, as well as multi-layered screens of the cabins, installed on the side of the source, can be used for this purpose. When there are no such screens, the distance between the annihilating power source and the cabin should be thousands of kilometers, which is not feasible,

The technological difficulties connected with designing a "rod-type" screen of a galactic craft obviously can be overcome if we find how to obtain a powerful (in our example, up to $15.6 \cdot 10^3$ billion kW) means of radiation of a certain wavelength $\lambda$, without using special electric power stations, which would have to have absolutely fantastic specific weights, on the order to $25 \cdot 10^{-10}$ kg/kW in our example.

The optical shield is a more "finally-divided sieve", which reflects a greater amount of the emission spectrum. Therefore, chaotic energy processes can be used directly in a quantum craft with optical screens. We have already mentioned some difficulties /173 in designing it, which seem to be insurmountable. However, as with the rod-type screen, favorable solutions may be obtained by increasing the size.

The possibilities of designing a "photon" screen were recently reexamined in a study by a group of Soviet engineers.[10] The authors based their discussions on the condition of equilibrium between the absorbed and emitted energy in the screen.

If we assume that a certain screen has a constant loss (absorption) factor, then, with an increase in the energy incident on it from the source, the previous amount of this energy is absorbed in the screen and emitted by it. However, every new equilibrius regime naturally corresponds to a higher absolute temperature of the screen.

After simple convergence of (3.1) and (3.20) for $\varepsilon = 1$, the equation determining the specific pressure on the surface of a plane screen can be written in the following form:

$$p = \frac{\sigma_0}{c} T^4 \frac{1+R}{1-R}. \tag{3.30}$$

[10] Kaznevskiy, V., Yu. Merkulov and I. Fatkin: The Shield of a Photon Engine. Aviatsuja i Astronautika, No. 2, 1963.

Table 6 and the graph in Figure 43 were calculated by using this formula. The table includes data on the area and equivalent diameter of screens for "maximal" and "minimal" spacecraft. It can be seen that the greatest amount of power can be received and reflected from a surface made of tungsten. The evaporation of tungsten under vacuum at high temperatures was not considered in the calculations. Considering the flight time, we can correct the requisite thickness of the screen and its temperature.

To guarantee the necessary pressure at the highest permissible temperature of the screen, we must have a definite value of the reflection factor *R*. It depends on the light wavelength. Let us remember that the wavelength decreases with an increase in the temperature of the emitting heat-source. For a wavelength less than $4 \cdot 10^{-5}$ cm = 0.4μ, or the lower boundary of the visible spectrum of electromagnetic waves, the reflection factor decreases abruptly. This forces us to limit the temperature of the source, which brings about an undesirable increase in its size. In any case, the source should emit waves which are best reflected by the screen.

TABLE 6. EFFECT OF THE MATERIAL ON THE SIDE OF AN OPTICAL SCREEN.

| Indices | Silver | Iron (with Coating) | Berrylium (with Coating) | Molybdenum (with Coating) | Tungsten (without Coating) | Tungsten (with Coating) |
|---|---|---|---|---|---|---|
| Temperature, °K | 870 | 1650 | 1420 | 2600 | 3300 | 3300 |
| Reflection Factor | 0.95 | 0.99 | 0.99 | 0.99 | 0.6 | 0.99 |
| Loss Factor | $5 \cdot 10^{-2}$ | $10^{-2}$ | $10^{-2}$ | $10^{-2}$ | $4 \cdot 10^{-1}$ | $10^{-2}$ |
| Weight, $m^2$, for Thickness of $10^{-2}$ mm, kg | 0.105 | 0.078 | 0.018 | 0.102 | 0.193 | 0.193 |
| Specific Pressure, $g/m^2$ | 0.43 | 29.2 | 15.9 | 178 | 9.2 | 450 |
| Relative Weight, kg (screen)/kg (pressure) | 242 | 2.65 | 1.13 | 0.57 | 21.0 | 0.425 |
| Relative Area, $m^2$ (screen)/kg (pressure) | 2330 | 34.2 | 63 | 5.6 | 109 | 2.2 |
| Requisite power of Emission, | | | | | | |
| $\frac{Kcal}{m^2} \cdot 10^{-3}$ | 0.3 | 20.7 | 11.2 | 125 | 65 | 317 |
| $\frac{kW}{mg} \cdot 10^{-4}$ | 0.13 | 8.8 | 4.76 | 5.35 | 2.76 | 135 |
| "Minimal" Spacecraft | | | | | | |
| Screen Area, $m^2$ | $16.3 \cdot 10^7$ | $2.39 \cdot 10^6$ | $4.4 \cdot 10^8$ | $3.92 \cdot 10^5$ | $76.3 \cdot 10^5$ | $15.4 \cdot 10^4$ |
| Equivalent Diameter, m | $1.02 \cdot 10^4$ | $1.24 \cdot 10^3$ | $1.68 \cdot 10^3$ | $5.02 \cdot 10^2$ | $22.1 \cdot 10^2$ | $3.14 \cdot 10^2$ |
| "Maximal" Spacecraft | | | | | | |
| Screen Area, $m^2$ | $12.1 \cdot 10^9$ | $1.77 \cdot 10^8$ | $3.27 \cdot 10^8$ | $29.1 \cdot 10^6$ | $5.66 \cdot 10^8$ | $11.4 \cdot 10^6$ |
| Equivalent Diameter, m | $8.8 \cdot 10^4$ | $1.06 \cdot 10^4$ | $1.45 \cdot 10^4$ | $4.32 \cdot 10^3$ | $1.9 \cdot 10^4$ | $2.7 \cdot 10^3$ |

The highest permissible computed specific pressures are plotted on the graph (Fig. 44) as a function of the temperature of the source, which is determined by the requisite emission wavelength. In this case, the length itself is determined by the value of the reflection factor of the screen. The graph indicates that it is important to find a method of reflecting short waves, high frequenceis ($\lambda < 0.4\mu$).

If we take a tungsten screen with a special coating guaranteeing a loss (absorption) factor of $\xi$ = 0.01, i.e., $R$ = 0.99, then the specific pressure on the screen, for a temperature of the source of around 10 000° K, is 250 g/m$^2$ /176
on the lower limit of temperatures for tungsten (see Point B 2700° K), and, for the "minimal" spacecraft, there must be a screen with area of $2.8 \cdot 10^5$ m$^2$, i.e., the diameter of the equivalent screen is equal to 420 m. In this case, the area of the screen for the "maximal" spacecraft is $5.2 \cdot 10^6$ m$^2$ and the diameter is 1820 m. The areas of the screens obtained from the calculations were found to be of the same order as those for cold "rod-type" screens, for loss factors of $\xi = 10^{-6}$, i.e., permissible for rod-type screens.

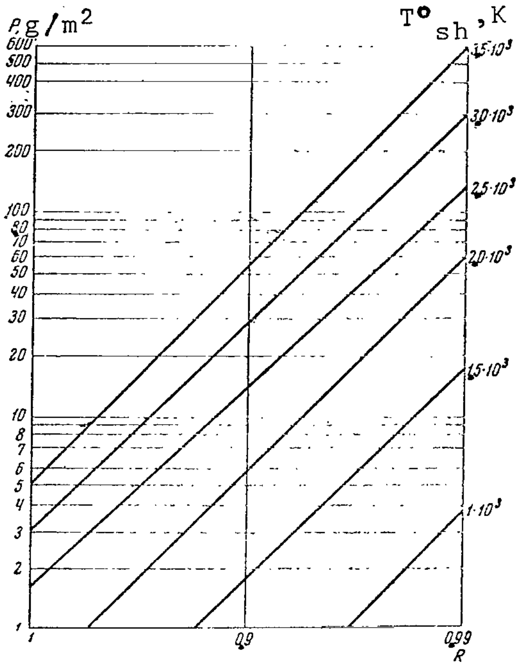

Fig. 43. Dependents of Light Pressure on Reflection Factor for Different Temperatures of an Optical Shield.

The authors also examined the effectiveness of different shapes of screens. It was assumed that the radiation source had the shape of an elongated cylinder and the screens were cylindrical surfaces. Since the pressure at each point of the screen acts along the normal to its surface, while the radiation falls on the screen from the center (see Fig. 44), then at $R$ = 1 some of this radiation does not generate thrust. Integration of the pressure over the entire screen (the depth of the screen is limited to an angle of 180°) yields a screen factor $k_s$, or ratio between the thrust of the screen and the thrust which could be produced when all of the energy source is used, for a clean screen and a plane source.

For a parabolic screen $k_s \approx 82\%$, and for a round one $k_s \approx 64\%$. However, the length of the arc of the parabolic screen, which means its weights, are found to be greater than those for a round screen. Moreover, a temperature gradient which has an unfavorable effect on the strength arises along the edges of the parabolic screen, in relation to its central section. Therefore, in the cases when the screen is large and its weight can be determinant in a selection of the design, preference should be given to the round screen.

However, we should finally mention that the temperature of screens of the types under investigation is very high and, obviously, extreme difficulties in guaranteeing their endurance, particularly under the conditions of evaporation under vacuum, are unavoidable.

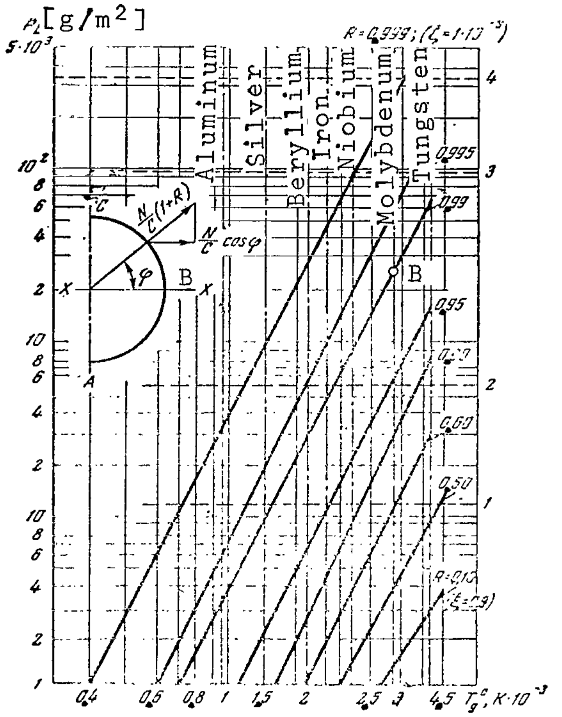


Fig. 44. Dependence of Pressure on Screen on its Temperature and Material for Different Reflection Factor R of the Material. (1) $T = 5 \cdot 10^3$ °K, $\lambda = 0.6$; (2) $T = 7.25 \cdot 10^3$ °K, $\lambda = 0.4$ (Lower Limit of Visible Spectrum); (3) $T = 15 \cdot 10^3$ °K, $\lambda = 0.2$.

A metal film of a few microns /177
in thickness which reflects photons, very tempting because of its lightness, evaporates during the very first month of operation. The middle surface should be supported by the grid, so that the load from the thrust on the screen is received. The weight of the screen of the photon quantum craft is more than that of a quantum craft operating on long waves, since the weight of the film is added to that of the grid of the rod-type screen. It is also very difficult to keep the entirety of the reflectivity of a thin screen which has a huge area at velocities around the speed of light and during interactions with the particles of the interstellar medium.

Let us now investigate the possibilities of an electromagnetic reflector. It is well known that, under certain conditions,
the annihilation of a positron /178
and electron in a high-intensity magnetic field may release not two $\gamma$-quanta scattering at large angles in opposite directions, but one quantum. In this case, the field in which the annihilation took place receives the output pulse. This field could also play the role of the screen.

K.P. Stanyukovich pointed out the fundamental possibility of producing a high-power annular magnetic field which could play the role of a "magnetic mirror", or, more precisely, a unique electromagnetic core. The "combustion chamber" and nozzle of the spacecraft would probably be equipped with reflectors and a "magnetic confinement" of this nature.

What should the magnetic reflector be like?

The pressure of the magnetic field is expressed as

$$P_m = \frac{\mu H_f^2}{8\pi}, \tag{3.31}$$

where $\mu$ is the coefficient and $H_f$ is the intensity of the magnetic field.

The pressure of a radiation flux (flux of particles), which tends to burst beyond the boundaries of the magnetic mirror,

$$P_p = \frac{1}{3} \rho_p c^2, \tag{3.32}$$

where $\rho_p$ is the density of the flux of particles.

The following condition must be satisfied to construct the screen:

$$\frac{\mu H_f^2}{8\pi} > \frac{1}{3}\rho_p c^2. \tag{3.33}$$

The last relationship allows us to evaluate the field intensity necessary for reflection of a particle.

For example, at $\mu = 1$ and $\rho_p = 10^{-10}$ g/cm$^3$, we find that $H_f \approx 9 \cdot 10^5$ oersteds. For low densities of radiation, we can decelerate the particles composing it by a magnetic field at a distance from 10 m to 1 km.

Deceleration can also be attained with the aid of an electric field. Watching the straight-line motion of a charged particle (for example, meson) in a decelerating electric field all the way to its complete stop, we can find the value for the energy of the field which provides for complete deceleration:

$$E_f = \frac{\varepsilon_p}{ect}, \tag{3.34}$$

where $\varepsilon_p$ is the energy of the particle. Particle energy on the order of $10^{-3}$ erg $= 6 \cdot 10^8$ eV $= 600$ MeV, particle charge (equal to charge of the electron) of $e = 4.8 \cdot 10^{-10}$ g$^{1/2}$ cm$^{3/2}$ sec$^{-1}$, and time until the stop of the particle of $t = 10^{-6}$ sec, are characteristic of the annihilation process. /179

Then $E = 1.8 \cdot 10^6$ V/m. In this case, the path of the particle is also on the order of several hundreds of meters or kilometers.

As K.P.Stanyukovich noted, the combined effect of an electric and magnetic field guarantees deceleration and reflection of the particles over a much smaller path than the separate action of the field. A relatively small amount of all the energy for annihilation is sufficient for reflection of a large amount of the radiation flux. Thus, only an insignificant amount of the total energy, and neutral particles, of which there are tens of times less than all the particles producing the radiation flux, fall on the optical mirror. Therefore, it is basically possible to construct an electromagnetic screen.

Finally, let us discuss the possibility of the so-called "plasma" or electron mirrors. In looking for ways to increase the reflectivity of screens in relation to the high-frequency electromagnetic vibrations, the German researcher E. Sänger suggested that the concentration of electrons in the material of the screen be increased. This method, in particular, will aid in increasing the reflectivity of the optical screens under investigation.

A further development of this idea was the suggestion that the mirror be made in the form of rather dense electron or plasma clouds. Since high-frequency radiation is gradually refracted and reflected from an electrically conducting medium, this method seems promising.[11]

The density of the electrons in the "screen-cloud" should be at least $10^3$ times greater than that in solid metals. However, colossal pressures approximating the pressures at the epicenter of a nuclear explosion, in particular, are necessary to produce an electron cloud of this density. This situation is sufficient to imagine the difficulty of producing a plasma mirror. Nevertheless, the possibilities of plasma mirrors should be studied. Other methods of constructing the screens of a spacecraft have also been proposed.

Developing the idea of K.P. Stanyukovich, we can suggest a /180
combination screen. The fact is that none of the proposed screens can completely reflect the multiplicity of emissions incident on it. At the same time, each of them can handle the reflection of waves of a certain length. Thus, in addition to the studies looking for converters which yield radiation at a definite wavelength, it may also prove fateful to analyze a combination screen consisting of different types of screens, each of which reflect waves of a certain range. This combination screen would reflect a wide range of waves emitted by an annihilation source.

Obviously, radio engineerings have the last word in the design of the screen-deflector - one of the principal elements of the engine of a galactic craft.

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[11] E. Sänger. Über das Richtproblem der Photonenstrahlautriebe und Waffenstrahlen. Munich, 1959; E. Sanger. Missiles and Rockets, March 27, 1961.

The solution to the problem of constructing the energy source and converter which steadily emits electromagnetic waves of a definite frequency range is just as important.

The annihilation source system supplying a quantum accumulator with radiant energy is of interest. This generator could be allowed by a narrow-band beam of radiation at a wavelength which a specially selected reflector could reflect.

The cited ideas on the fundamental possibilities and waves of designing a spacecraft still do not give a clear idea of its technological details and structural forms. However, they are sufficient to understand the basic designs of galactic craft (Fig. 45).

Obviously, the spacecraft will not be the same, and perhaps will be far from the same, as we could imagine today. However, it is basically possible to construct such apparatus, and they undoubtedly will be constructed.

In 1958, K.P. Stanyukovich devised the idea of using the mass of a large asteroid as the working fluid for a spacecraft, and also as the principal stage of the spacecraft. In a gigantic engine capable of converting the rest mass of an asteroid into electromagnetic radiation and ejecting the jetstream with the aid of annular magnetic fields would drive part of the asteroid into the system of /181
another star. The idea of using the matter of asteroids is of interest, since the astronauts would not have to think about reaching reserves at a docking station. However, we must keep in mind that an increase in the takeoff mass would require a substantial increase in thrust, which means an increase in expenditure of the mass, for a prolonged flight.

However, each bold attempt at overcoming the difficulties in hindering the construction of spacecraft is, in our opinion, justifiable.

## Assemblying the Galactic Craft and Communicating With It.

The conception of a spacecraft in outer space with the aid of an orbital station, the prototype of which is possibly the OMBS which was described above, will require that the details of the station, as well as the details and units of the craft, be put into orbit precisely. They should all be concentrated at one side for assembly.

The galactic craft could be made in a way similar to the manner in which standard houses are now made, using large prefabricated blocks and panels. It is probable that, by that time, many of the details of solar rockets and the cargos transported by them will be standardized. These units, cabins, empty fuel tanks, and bodies of the last rocket stages will also serve as the principal structure of

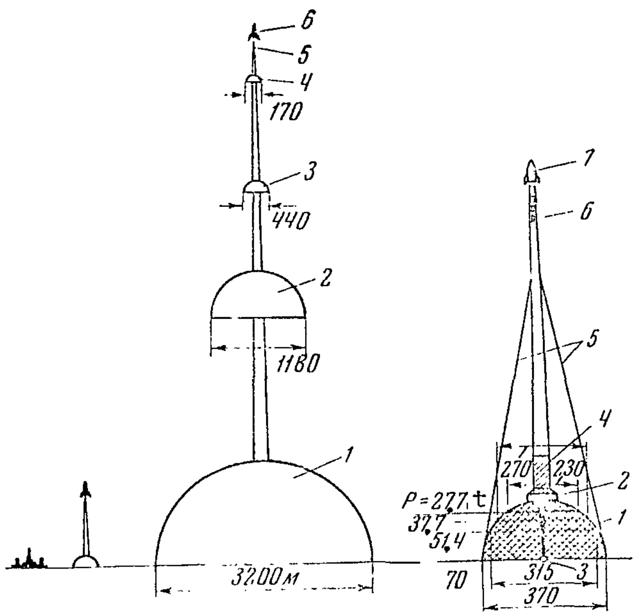


Fig. 45. Perhaps This Is the Way Spacecraft Will Look. At Left--Example Side Dimensions of the "Minimal" and "Maximal" Spacecraft Compared to the Building of Moscow State University at $\xi = 10^{-6}$: (1-4) Screens of the First, Second, Third and Fourth Stages; (5) Greenhouses; (6) Interplanetary Rocket with Crew Cabin. At Right--"Minimal" Spacecraft on Large Scale: (1) Screen-Deflector of Electromagnetic Waves, Quanta (we have indicated the First, Second and Third Screen Sections Which Can Be Used and Fired at the End of Each Subsequent Acceleration or Deceleration Stage); (2) Apparatus Which Convert the Rest Mass of a Substance into Material Electromagnetic Radiation; (3) Radiator; (4) Rest Mass Reserve; (5) Points of Attachement; (6) Greenhouses; (7) Interplanetary Rocket with Cabin.

the spacecraft. Naturally, a certain number of elements will be made specially for it. /182

The spacecraft assemblers will be working some of the time under the conditions of outer space. For protection from the effects of overheating, cold and dangerous radiation, special outfits could obviously be used. For outside work, cabins with small jet engines and remote-control arms could also be used.

Curved mirrors and compact lenses concentrating solar rays will become the welding apparatus for the space welders using the achievements of the heliotechnology. The welded joints obtained under the conditions of the high vacuum of outer space will guarantee complete pressurization of sections of the spacecraft. After the section is pressurized, the erection of its inner elements could be carried out in an artificially induced atmosphere. Its workshop would be assembled in the first sections of the spacecraft, and their equipment would be used to construct the rest of the craft.

It seems necessary to send not one but several galactic crafts simultaneously on an interstellar voyage. This will increase the reliability of the solution to the problem and will be of aid to all of the craft, increasing the chances of a happy ending to the expedition. Some ideas on the organization of a flight to Mars suggests that at least two crafts should be sent on the trip. If one of them were harmed, its crew would transfer into the cabin of the second. We should also mention certain other circumstances which are specific for spacecraft. /183

The power plant of the spacecraft, and its on-board apparatus and equipment should be designed for a very long period of operation (at least 50 years). They should preserve their reliability under the conditions of very long operation at different accelerations, as well as under the conditions of weightlessness. The power supply sources should be just as long-lived. Obviously, there must be a supply of the most critical elements of the spacecraft from two sources: from the principal engine apparatus and from an autonomous emergency power source, for example, an atomic energy plant, which guarantees the operation of mechanisms in the craft when the principal engine breaks down.

It is also absolutely necessary to have a reliable two-way communication between the craft and the Earth. This communication is needed not only to transmit information, but also so that the crew will not feel isolated from the Earth and from the society which sent them.

Even during the first flight, Yu. Gagarin provided a reliable space radio communication. There is good communication between the craft of V. Nikolayeva-Tereshkova and V. Bykovskiy. Television transmissions were sent from spacecraft with the first unmanned television apparatus.

The record range of radio communications, reached during sessions with the Soviet interplanetary station directed toward Mars, reached 100 million km. An apparatus which allows radar display of Venus, Mercury, Mars and Jupiter was designed in the U.S.S.R. under the direction of the Academician V. Kotel'nikov. For Jupiter, the radio-frequency waves reached 1 billion 200 million km.

Doubtless there will be radio communication with craft whose course lies within the boundaries of the Solar System. It is immeasurably more difficult to have communications with a galactic craft. Even if there is such communication, it will be surprisingly ineffective--if it takes 8.54 years for a two-way exchange of communication between craft, for example, in the region of Proxima Centauri and the Earth. The radio-frequency waves take that long to travel both ways. Moreover, they must overcome numerous obstacles. /184

In the Earth's atmosphere, there is an "atmospheric window" through which electromagnetic emissions of a definite wavelength penetrate; there are also extremely diversified atmospheres (which also means bounded atmospheric windows) around some other planets. This is the first "circumplanetary" obstacle. The free electrons contained in interstellar clouds also produce unique ionospheres which absorb and reflect the radio waves.

Fluxes of cosmic radio emission, the emission of interstellar gas and neighboring galaxies are all sources of interference for receiving apparatus. Finally, belts of increased radiation, which encompass the Earth like a halo and have openings only in the regions around the Pole, can have a harmful effect on the operation of the radio apparatus.

We need not only stations for radio communication with the craft, but also stations which can detect meteors and solve problems of navigation, etc.

To send radio signals over interstellar distances, there must be superpowerful transmitters and antennas with hugh amplification which emit a narrow beam of radio waves. This means that the antenna must be tuned precisely. Moreover, the corresponding points must be on a line of direct visibility of intermediate relay stations must be used.

Radioastronomy has made an invaluable contribution to space radio engineering. The larges modern rotary antenna, installed at Jodrell Bank (England), has a parabolic mirror with a diameter of 73 m. The fixed antenna of the Pulkovo Observatory extends to 120 m. We should mention that the diameter of antennas which can be erected on planets with atmospheres is limited in connection with the distortion of the wave front in the atmosphere. Thus, for a wavelength of 3 cm, the largest diameter of the paraboloid is 150 m under the conditions of the Earth's atmosphere. /185

Obviously, we must send communication stations beyond the atmosphere of planets to artificial satellites or space bodies, like the Moon, which do not have an atmosphere. In any case, the principal transmitter on the base should be most powerful and perfected, which will increase the range for the limited power of the on-board apparatus. It is possible that supereconomical, superpowerful transmitters will be constructed fro the radio communications apparatus acting on galactic craft in outer space, where almost an ideal vacuum reigns.

When the distances over which radio communications must be carried out increase, the power unit on board the craft must be increased. We should also keep in mind that the power necessary for the operation of the transmitters increases when their tasks become more complicated. Thus, to transmit televised images from a satellite to the Earth, there must be a power which is 1000 times greater than that for a simple direction finding. It is doubtless that, when the principal problem, that of providing the power demands of a quantum engine, is solved, tens of thousands of kilowatts may be used for communication.

However, in the case of approaching the speed of light, i.e., rate of propagation of the radio waves themselves, there are effects which limit the possibilities of reliable radio communication. For example, when moving away from our planet, the real power of a signal received on the Earth is more diminished than if this decrease were caused only by an increase in distance. Thus, for a speed of withdrawal which is half the speed of light, the power of the signal decreases by a factor of five. Naturally, the signal-"noise" ratio of the Galaxy, which remains roughly constant, will decrease, and the "noise" will interfere more.

The craft can maintain two-way communication with the Earth only when it has rather powerful receivers and high-sensitivity transmitters with insignificant natural noise. The radio stations which have now been designed on the basis of quantum amplifiers will aid in increasing the sensitivity of the apparatus by a factor of 100. Obviously, thin and extremely powerful beams of electromag- /186 netic waves and light rays will be obtained by using them, and radio communication will be carried out over distances of several light years.

When the craft "withdraws" from the Earth at a velocity on the order of the velocity of the radio waves, the signal frequency on the ground also shifts. For example, the sounds received from the craft will become lower and may even go into the infrasound range.

When galactic crafts withdrawing from the Solar System move at a velocity which is very close to the speed of light, communications will become one-way. It will too long for signals from the Earth to reach the spacecraft. At the same time, information can be sent from the craft to the Earth. In this case, together with the automatic systems transmitting information to the Earth without dependence on the crew, there should also be transmission of reports and information from the astronauts themselves.

For the segment of the course where the flux of quanta ejected by the screen-deflector of the engine is directed toward the Solar System, it may be possible to carry out transmissions superposing regular oscillations over this flux. In any case, if this beam is received by radio apparatus in the Solar System, it will indicate how the engine of the craft is operating.

However, it is not only radio communication which will guarantee the transmission of reports to the Earth or to the base-satellite in the Solar System. For example, at the beginning of the course the crew will be able to form artificial signal comets (a successful experiment with the automatic production of such a comet was carried out during the flight of the first Soviet space rocket). Finally, it is not impossible that automatic "retrorockets" with most valuable information, equipped with relatively small quantum engines, may be sent into the Solar System. The structural elements of stages which should be ejected during acceleration or deceleration of a spacecraft may possibly be used for assembling such rockets.

## 4.

## THROUGH THE ARMOR OF TIME AND DISTANCE

### Paradox? No, Development!

When the quantum rocket is constructed, man will have taken a definite step forward in mastering not only space but also time. /187

According to one of the conclusions of A.E. Einstein's special theory of relativity, time depends in particular on the constant velocity at which a certain body moves in relation to an unmoving body. As this body moves more rapidly, less time passes for an observer on it, relative to the time which has passed for a stationary observer. The relative decrease in the time interval for a moving body is substantial only at velocities which are close to the speed of light. Therefore, we do not notice it on the Earth during our everyday life. However, this manifestation of the laws of nature alone allows us to be assured that man will penetrate the depths of outer space, hundreds of light-years away from us.

Underlying the special relativity theory is Einstein's principle of relativity, which states that the laws of electromagnetic, thermal, mechanical and other phenomena are identical in all inertial systems, i.e., systems in a state of absolute equilibrium and straight-line motion. This means that no experiments inside a single system, without including other neighboring systems, will allow us to determine whether or not it is in motion. Neither can /188 this be done by examining the electromagnetic field (light is also an electromagnetic field), since it propagates, in any inertial system, under vacuum in all directions at one velocity - roughly 300,000 km/sec. Let us take this assumption and examine some results of the restricted, or special theory of relativity.

Let us assume that the spacecraft which maintains a constant ratio between its mass and the thrust of the engine is launched from some space station. For the ground observer, the intrastar distances remain constant. At the same time, as the spacecraft approaches the critical velocity - the speed of light in vacuum - the observer on the Earth would conclude that the spacecraft is acquiring less and less of a velocity gain and that its acceleration is decreasing. However, for the spacecraft itself (i.e., in that instrument reading system in which the rocket is not moving), there are no decreases in acceleration, since $\frac{M}{P}$ = const.

This happens because, as the spacecraft is accelerated, longer and longer time intervals elapse in the ground reading system relative to the time intervals passing on the spacecraft. Only in this case can we find a logical reason for the observed decrease in the acceleration of the spacecraft.

On the other hand, for the observer in the spacecraft - the constant acceleration system - the rate of increase in velocity and, consequently, the velocity itself, continued to increase uniformly in time.

Nevertheless, the permissible critical flight speed may not exceed the speed of light in vacuum. This means that, in approaching the speed of light at a constant acceleration, the distances should begin to grow shorter for the galactic craft. Only in this case can its cross them in shorter and shorter time intervals. This is also the actual flight time for calculating the amount of fuel necessary for the craft.

That is why the ground observer, determining the velocity according to distances measured from the Earth, but the time and duration of the flight according to the clock on the spacecraft might conclude that the spacecraft was moving "several times faster than the speed of light". Actually, the speed of light was not surpassed, since the distances spanned by the craft as well as the flight time, were shortened in the system of the spacecraft, while the ground observer simply used a different meter, or a /189
different clock.

Let us emphasize that an inertial system, such as the Earth moving in its orbit, and the system of the spacecraft are inequitable. Before attaining a velocity on the order of the speed of light, the spacecraft must be accelerated and then decelerated during re-entry, i.e., its velocity must be changed, while its base line must continue to move uniformly.

It is extremely difficult for us to comprehend the immutability of the facts following from the relativity theory on the basis of the ideas to which we are accustomed.

The seemingly paradoxical results of the relativity theory can be explained by the fact that the distances between the same material points and the time intervals between the same events vary in different systems, and are converted according to a definite law during a transition from one system to the other. This law was obtained from the condition of a velocity limitation, which is bound to the speed of light in vacuum, and it allows us to explain the experimentally established fact that the speed of light is constant when measured by its propagation with and counter to the movement of the Earth.

In our days, the paradox that time is relative to velocity has been confirmed by a large number of observations on changes in the microworld and, in particular, on cosmic particles moving at a velocity close to the speed of light. Thus, for cosmic particles moving through the Earth's atmosphere at velocities near the speed of light, the time intervals between their collisions, for example, can be thousands of times more brief than the time intervals between the same collisions in the Earth's system, which leads to the numerous distinctive features of the behavior of such particles.

The time interval during which cosmic particles fall to the Earth also depends on their velocity, and these times agree with those calculated according to the formulas of the relativity theory.

Not only has the relativity theory been established experimentally, but also it has been applied in engineering and technology. None of the atomic particle accelerators or nuclear reactors could operate if the postulates of the relativity theory were found to be invalid, since these devices are designed on the basis of this theory.

Distance and time are converted into functions of the veloc- /190
ity according to the formulas of the special relativity theory in the following way:

$$l_a = \frac{v_K t_K}{\sqrt{1-\left(\frac{v_K}{c}\right)^2}}, \qquad (4.1)$$

$$t_a = \frac{l_K}{1-\left(\frac{v_K}{c}\right)^2}, \qquad (4.2)$$

where $l_a$ and $t_a$ are the distance and time in the system of the observer at rest (on the Earth); $l_k$ and $t_k$ are the same factors in the system of the observer in motion (in the rocket); $v_k$ is the velocity of the latter system (relative to the Earth).

Thus it can be seen that, for the stationary observer, the spacecraft traverses a distance of $l_a = v_k t_a$, and longer time intervals pass for him (on the Earth) than on the spacecraft. Thus, more than 2.9 years pass on the Earth for one year of flight on a craft at a velocity of 94% the speed of light.

Until now, we have been examining the immutability of a certain consequence of the special relativity theory. However, if we connect the system of coordinates, the observer's reading system, not with the inertial body (in our case, with the Earth), but with the spacecraft, then we must turn to the general theory of relativity to find the particular characteristics of the course of time in these two systems.

The general relativity theory establishes a deeper relationship between matter, space and time than Newtonian physics. In the latter, space and time did not depend on the density of matter. It is held that the geometric properties of space and the passage of time are determined by the density of matter in any region of space. Where there is an accumulation of masses and, consequently, an intensive gravitational field, the space is deformed and curved, and the slowing of clocks effect occurs.

Thus, the time interval between two events taking place in the system of the Sun is shorter than the time interval between the same events on the Earth, since the gravitational mass of the Sun is much greater than that of the Earth, and the shortening of time /191
on the Earth, due to its movement relative to the Sun, is twice inferior to the shortening of time on the Sun due to the gravitation.

Gravitation and deformation of space arise simultaneously when massive bodies are present. The Earth is attracted to the Sun, as if time were attempting to slide down into a gravitational cavity formed in space. Naturally, this is only a superficial analogy, since the deformation of space and time actually does occur.

The intrinsic time in a system passes more slowly when the absolute value of the gravity potential $\phi$ increases (where $\phi < 0$), and when the gravity field at a given point is stronger. The reading of time $\tau$ in the gravity field is connected with the reading of time $t$ outside the field by the following equation:

$$\tau = t\sqrt{1-\frac{2\varphi}{c^2}}. \qquad (4.3)$$

The so-called Einstein principle of equivalence, which is of a local nature, holds that all physical passages take place in an identical manner under identical conditions in an inertial and rather small reading system in uniform constant gravity fields, as well as in a rather small reading system moving at a constant acceleration when there is no gravity field. In other words, the gravity forces are identical to the forces of attraction. Because of this, for example, after accelerating a craft in space we can produce an artificial gravity field. However, if we allow the craft to move freely in a uniform gravity field, this field could be artificially "nullified". Therefore weightlessness, for example, is also observed in an artificial earth satellite. The gravity fields caused by the presence of large masses, which decrease in intensity, disappear at large distances from them. The artificial fields due to accelerations do not have this property.

In accelerating or decelerating a craft, the direction of the gravity potential changes at its location. It goes opposite to the direction in which the craft is accelerated or decelerated, i.e., it is directed where the inertial force is directed. Consequently, the gravity potential is greater there, and where the /192
gravity potential is greater, time passes more slowly. Moreover, the gravity potential increases with an increase in the force of gravities and in the distance between the points where they were applied.

Let us examine the passage of time on the Earth from the point of view of observers on a "minimal" craft sent to Proxima Centauri.

In accelerating a craft leaving the Earth, the inertial force impeding acceleration is directed toward the Solar System and, consequently, the potential of this force is greater at the location of the Earth, which means that time passes more slowly on the Earth. However, the distance, therefore the difference in the gravity potentials between the Earth and the craft, are relatively small; hence the slowing of clocks is also small.

But now half of the distance to Proxima Centauri has been crossed. The craft is turned toward the stars by the engine jets. Now the inertial forces impeding deceleration are directed away from the Solar System, away from the Earth, toward the craft (the potential of this force is greater in the system of the craft) and there is a slowing of clocks on the craft, compared to the Earth. Since the distance between the craft and the Earth is vast, the river of time on the Earth becomes an impetuous stream washing away, say, weeks of Earth life into days of flight of the craft.

On the return trip, the change of time intervals is repeated in reverse order. At a large distance from the Solar System, acceleration during the return is carried out towards the Solar System, which means that the inertial force is directed from the Solar System to the craft where much shorter intervals will occur at a great distance from the Earth (a great difference in gravity potentials), and there will be a much greater slowing of clocks than on the Earth.

Then, in the deceleration during the approach toward the Earth, the course of time on the Earth is retarded compared to that on the craft, but the craft is relatively close to it, and the gravity potential is small, so that fast the Earth time cannot become equal to that on the craft. As a result, much more time passes on the Earth during the entire voyage than on the spacecraft.

In evaluating the same phenomena from the point of view of ground observers, the slowing of clocks on the Earth would have the same result as from the point of view of the crew on the craft.

The relative change in time intervals in the case of a flight /193 at an acceleration $a$ for a distance between the spacecraft and the Solar System $l$ is expressed in first approximation by the following equation:

$$\frac{\Delta t}{t} = \frac{al}{c^2}. \tag{4.4}$$

For a small acceleration, the relative change in time intervals is small even at large distances. Actually, as we suggested earlier for the case of the flight of a "minimal" spacecraft to Proxima Centauri, let us assume that $a$ = 0.2 m/sec$^2$, $c = 3 \cdot 10^5$ km/sec = $3 \cdot 10^8$ m/sec. Then, for the distance in the acceleration phase up to half of the way to Proxima Centauri $l = 2 \cdot 10^{16}$, we can find the following slowing of clocks on the Earth, compared to that on the rocket:

$$\frac{\Delta t}{t} = \frac{0.2 \cdot 2 \cdot 10^{16}}{9 \cdot 10^{16}} \approx 0.04 \approx 4\%.$$

On the second segment, at the end of deceleration near Proxima Centauri, when the distance $l$ increases twice, the speedup of the course of time on Earth in relation to the time on the craft is 8%, and 4% more time passes on the Earth during a one-way flight than on the rocket. This regularity in the sense of time passes is preserved during the return trip. In the final analysis, there is a time gain for the rocket crew of 8% during the entire round-trip flight, i.e., 56.8 years:

$$\Delta t = 0.08 \cdot 56.8 = 4.54 \text{ years.}$$

The relative change in the passage of time intervals increases abruptly during substantial accelerations. Thus, for an acceleration of $a$ = 9.81 m/sec$^2$, which is roughly equal to that of the Earth, in the first stage, up to the end of acceleration, the time passed on the Earth is less by

$$\frac{\Delta t}{t} = \frac{9.81 \cdot 2 \cdot 10^{16}}{9 \cdot 10^{16}} = 2.2 \text{ times.}$$

Correspondingly, at the end of the second phase, or deceleration, 4.4 more time passes on the Earth. In all, during a one-way flight, roughly 2.2 times more time passes on the Earth than on the rocket, and 4.4 times less time passes on the rocket during a two-way flight than on the Earth. /194

Figure 46 and Table 7 give calculated flight times for the Sun-Proxima Centauri-Sun course for two systems (the Earth and the rocket), as obtained by I.D. Novikov according to the following pattern: boost with acceleration of $a$ = 10 $g$ up to a velocity of $2.5 \cdot 10^2$ km/sec, coasting at that velocity, deceleration during approach to Proxima Centauri with repetition of the same stages during the return flight toward the Sun.[1]

TABLE 7. TIME ON THE EARTH AND IN THE ROCKET DURING A FLIGHT TO PROXIMA CENTAURI AND BACK, YEARS

| Stage | In the Earth System | | In the Rocket System | |
|---|---|---|---|---|
| | Earth | Rocket | Earth | Rocket |
| Acceleration away from the Solar System | 1.45 | 1.14 | 0.8 | 1.14 |
| Inertial Flights | 3.33 | 1.85 | 1.03 | 1.85 |
| Deceleration During Approach Toward Target | 1.45 | 1.14 | 4.4 | 1.14 |
| Stay in the System of the Target | 1.00 | 1.00 | 1.00 | 1.00 |
| Acceleration Toward the Sun | 1.45 | 1.14 | 4.4 | 1.14 |
| Inertial Flights | 3.33 | 1.85 | 1.03 | 1.85 |
| Deceleration During Approach Toward Solar System | 1.45 | 1.14 | 0.8 | 1.14 |
| Total | 13.46 | 9.26 | 13.46 | 9.26 |

Finally, we should pay special attention to the biological aspects of the relativity theory. In recently published comments on the clock paradox, this effect is "used" either to "lengthen" the life of astronauts so that there can be a deeper penetration into space during the lifetime of one generation, or to convince the readers that "even this is possible", or, finally, for the sake of entertainment with an actual fantastic subject.

In 1963, a group of scientists made the first scientific attempt to formulate the problem on the principles of constructing and using instruments to test the biological effect of the relativity theory.[2]

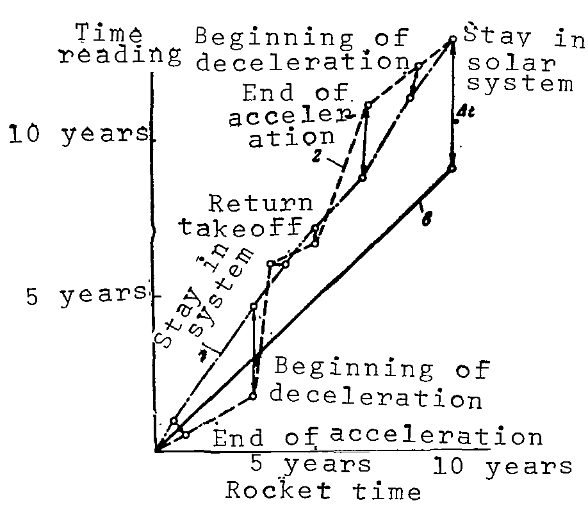


Fig. 46. Time Graph. (1) Earth Time in the Earth System; (2) Earth Time in the Rocket System; (3) Rocket Time in the Rocket System. /195

[1]See: Stanyukovich, K.P. and V.A. Brenshten: Interstellar Flights. Coll: Kosmos (Outer Space). Akad. Nauk. S.S.S.R., Moscow, 1963.
[2]See next page.

Micro-organisms capable of living on a craft for a long time without food or oxygen were suggested as the object of the investigation.

These micro-organisms, i.e., the butyric fermentation microbe, should be put in AMH-1 biocells, which have already been tested in flight on the second Soviet spacecraft, or other cells of this type. This cell guarantees the preservation of the spores of the micro-organisms for more than ten years, and their seeding according to signals from the Earth or from a programmed device. The biocell /196 then aids in recording the reproduction of the micro-organisms all the time until they reach a maximum concentration in the culture medium. A certain gas pressure is produced, depending on the period of reproduction of the microbes in the cell. The pressure pickup transmits all the dynamics of the pressure and, thus, the reproduction of the microbes, through the telemetric system to the Earth. The average period for a complete development cycle of a colony of micro-organisms can be taken as equal to 24 Earth hours, with 10% deviations, i.e., from 19.6 to 26.4 hours.

For a clearer representation of the effect of the clock paradox, the flight speed must be selected in such a way that 10% more time should pass on the Earth, i.e., roughly 29 hours, considering the theory. The control cell with a similar colony of microbes can be kept under identical space flight conditions on a satellite. To guarantee purity, the biocells should be shielded reliably from cosmic radiation. Using (4.4) it is easy to find that, to show the clock paradox in microbiology, the velocity of the craft should be 160,000 km/sec = $160 \cdot 10^6$ m/sec for a 24-hour uniform flight according to intrinsic time and, consequently, for 29 hours according to Earth time.

The authors rightly hold that to eliminate the effects of acceleration, the experiment should begin after this velocity is obtained.

Let us remember that, to reach a velocity of 160,000 km/sec for acceleration of $a$ = 1 m/sec$^2$, the rest of the space craft in kilograms should be constantly 1/10 of its mass, or should coincide with the mass in newtons, which obviously will be accompanied by great difficulties in the first stage "stellar craft construction".[3]

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[2]See: Zhukov. Verezhnikov, N., V. Kop'yev, I. Meyskiy, A. Pekhov, G. Tribulev and V. Yazdovskiy: The Biological Aspect of the Relativity Theory. "Aviatsiya i Astronautika," No. 2, 1963.

[3]Even for the "minimal" stellar craft, we assume the acceleration to be $a$ = 0.2 m/sec$^2$ and the thrust to be equal to 1/50 of its mass. In this case, more than 25 years would be needed only to accelerate up to $16 \cdot 10^4$ km/sec, i.e., to prepare for the experiment.

Then, the following time should pass before this velocity is gained:

$$t = 160 \cdot 10^6 = 16 \cdot 10^7 \text{ sec} \approx 5.1 \text{ years.}$$

and the apparatus should cover a distance of /197

$$L = \frac{at^2}{2} = \frac{1 \cdot (16 \cdot 10^7)^2}{2} = 128 \cdot 10^{14} \text{ м} = 12.8 \cdot 10^{12} \text{ км} .$$

Then, after 24 hours of flight at a velocity of $160 \cdot 10^3$ km/sec, the craft should traverse $160 \cdot 10^3 \cdot 24 \cdot 3600 = 13.8 \cdot 10^9$ km more. In all, the spacecraft will cover approximately 14 trillion kilometers. This means that it will be at a distance of 1.3 light years. Therefore, we must take into account that the signal on the results of the experiment will reach the Earth only 1.3 years after the experiment is completed.

We should mention that terminological inaccuracies still often bring about incorrect interpretations of the phenomena which take place with the biological objects when very high velocities are obtained.

It is often shown that, when certain velocities are reached, biological processes on a spacecraft take place more slowly than on the Earth, or that all the processes on a moving spacecraft supposedly occur more slowly than on the Earth, all the more slowly when the apparatus moves more rapidly.

We might have the impression that the life tempo on such a spacecraft slows down more and more as the velocity of the craft increases, as in a movie which is made at a fast speed and then projected at normal speed. The movement becomes smooth.... slow .... the heart beats less often.... life gradually dies away.

Actually, nothing like this takes place or could take place. All the natural phenomena i.e., plant growth, decay of isotopes, operation of the most accurate molecular clocks, everything on board the craft evolves and moves at the same tempo as on the Earth. Only if we use the time which passes on the Earth which is stationary relative to the craft do these processes observed from the Earth (if this were possible) seem to take place slowly.

However, for members of the crew and for the phenomena taking place in the spacecraft, it makes no difference what time interval passes on the Earth or any other astronomical object. In the craft, time changes according to its own clock. In this intrinsic time, all the processes, such as the beating of the heart, digestion and chemical reactions, take place in the same way as they did on the Earth.

Thus, receiving reports by some means on the life period passing on the craft, the scientists of the Earth who obtain information on the shorter life span enjoyed by the biological subjects on the craft, not because the biological processes took place more slowly, but because time passed more slowly on the craft. /198

The inaccuracies in terminology should not give rise to doubts concerning this repeatedly described relation between phenomena. Doubtless the laws which are valid for elementary particles are also valid for the highly-organized forms of matter which consist of these particles. As is well known, the general laws of nature apply equally to living and non-living bodies (the law of universal gravitation, the law of motion, etc.). Since all the bodies of the universe, including living organisms, consist of elementary particles, for the system in which the relativity theory is valid, identical laws of nature should act regularly on all bodies. Since physical relationships and interactions between unit particles are incomparably greater than the chemical and other processes bringing about the appearance of life, there is no reason to expect deviations in the "behavior" of biological subjects from the "behavior" of physical subjects evolving in correspondence with the theory of relativity.

In particular, we should not expect that a relative increase in the mass of atoms would affect the molecular structure of living cells. There is no relativistic increase in mass of atoms in the system of the craft on which the experiment will be carried out; therefore, it can have no effect on the molecular structures of living cells of the object under investigation. A relative increase in the mass of atoms of the object will be observed only in relation to the Earth, from the point of view of the ground observer. However, this can have no effect on the biological processes taking place on the craft itself.

We have no doubt that the experiment will completely agree with the relativity theory. Nevertheless it will be useful to carry out such an experiment. Its success would convince people of the universality of the law which is becoming an integral part of scientific and technological advances in our time.

The time will come when mankind will encounter its first galactic travellers, as we have encountered our first pilot-astronauts. At that time, a vast majority of people, certain that Einstein's theory has been proven correct in practice, will become accustomed to regular changes in time intervals, a contraction of the space traversed at velocities near the speed of light and certain values of the gravity potential. They will become so accustomed to these phenomena that the current misunderstandings concerning these effects will seem paradoxical. /199

## 94% THE SPEED OF LIGHT

So that an encounter with inhabitants of the planet of another stellar system may become probable, mankind should be able to reach at least several tens of thousands of star systems. There will be no further need to fly to a large number of them when preliminary investigations of their movement from the Earth show that they are without planets, or when it is established, after an intense study of their particular characteristics from the Earth, that the systems have planets but they clearly have no life. After a preliminary selection, there will be "only" hundreds of systems left where it can be supposed that life exists. The crafts of the prospectors of the universe should be directed towards them. If we discover a technologically developed civilization, particularly one with which we can establish radio contacts, a flight to it will, naturally, be especially important.

Let us attempt to estimate the minimal flight data capable of solving this principle problem for galactic craft. We will agree that the natural period for the voyage is limited to 50 years, or roughly the period of the creative life of a human. We can be sure that this period will increase during further ordering of our social conditions.

Let us assume that the maximum velocity which the stellar craft can develop does not exceed 94% of the speed of light (281.8 thousand km/sec). After attaining this velocity, the engine is turned off and the subsequent flight continues by inertia until most of the course is traversed, and deceleration begins during approach toward the system of the other star. Considering all the /200
cited conditions, the travel plan, plotted in the coordinates of the rockets, is that shown in Figure 47 (for example, Curve 2).

For a maximum flight distance, it is desirable to have the highest permissible value for acceleration of the rockets. It is clear that, the less time needed for acceleration and deceleration of the rocket, the greater distance it can cover, then moving at a constant velocity during a one-way flight for 25 years of the natural life of the astronauts.

Naturally, an acceleration yielding a weight equal to that on the Earth and corresponding to $g = 9.81$ m/sec$^2$ will be the most advantageous. However, as we have already mentioned, there are limitations in that, to obtain substantial thrusts from a quantum engine, extremely high-power emissions are required. This limitation can probably be eliminated to a great degree in the course of development of science and technology; however, it will determine the maximum permissible accelerations of the spacecraft in the foreseeable future. Therefore, in estimating the maximum flight distance, we must first base our discussions on relatively low accelerations.

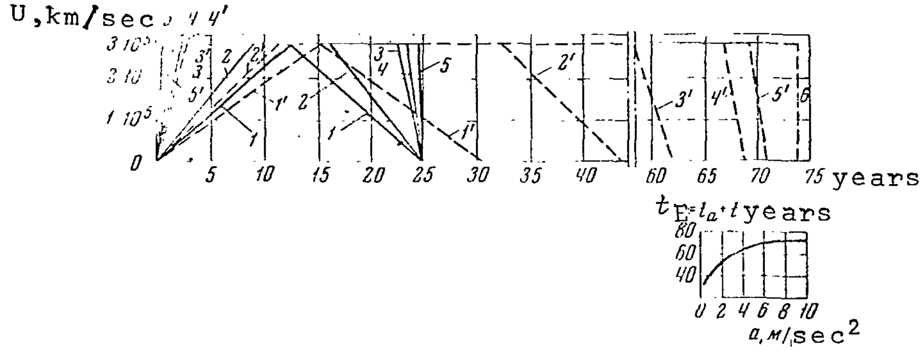


Fig. 47. Flight Patterns According to Time Passing on the Earth and in the Spacecraft, as a Function of the Allowable Acceleration at $t$ = 50 Years. (25 Years One-Way) and $v_k$ = 94% $c$.

The Solid Lines Show the Velocity According to the Time Passing in the Spacecraft, and The Dashed Lines Show the Same According to the Time Passing on the Earth.

(1-1') $a$ = 0.715 m/sec$^2$; (2-2') $a$ = 1 m/sec$^2$; (3-3') $a$ = 4 m/sec$^2$; (4-4') $a$ = 6 m/sec$^2$; (5-5') $a$ = 9.81 m/sec$^2$; hypothetical case $a = \infty$. Graph Below - Time Passing on the Earth, for the Flight Patterns of 25 Years Passing in the Spacecraft, as a Function of the Acceleration During the Booster Stage.

Let us begin our calculations with an acceleration of $g$ = 1 m/sec, and let us increase it to $a = g$ = 9.81 m/sec$^2$, which is equal to that on the Earth. /201

At $a$ = 1 m/sec$^2$, for acceleration up to a velocity of $v$ = 0.94, $c$ = 28.18·10$^7$ m/sec, we must have the following time: $t_k = \frac{v_k}{a}$ = 28.18·10$^7$ sec 9 years. Thus, there must be 18 years for acceleration and deceleration, and 7 years remains for flight at the maximal velocity.

In this period, how much time passes on the Earth? What distance measured from the Earth do the space travellers cover? To answer this question, we must first of all find how much time passes on the Earth during one acceleration(or deceleration) stage of the spacecraft. This problem cannot be solved in the way sometimes done in popular literature, by directly by using (4.2), which gives the Lorentzian time contraction, for calculations of the Earth time during different stages of accelerated movement.

Actually, $v_k$ is the final flight speed of the rocket relative to the Earth, and the direct application of this equation is possible only when the rocket moves at this constant speed. In acceleration of the spacecraft, the velocity is at first very low and, therefore, a substantial overstatement of the time passing on the Earth is unavoidable when the final velocity $v_k$ is used in (4.2). To obtain a correct result, (4.2) should be integrated with the change in velocity factor and converted into the following form:

$$t_a = \frac{c}{a} \arcsin \frac{at_k}{c}. \qquad (4.5)$$

To determine the intrinsic time, or the time passing on the rocket, for a known time $t_a$ it is easy to find the relationship:

$$t_{\text{к}} = \frac{c}{a} \arcsin \frac{at_a}{c} \approx \frac{c}{a} \ln \frac{2at_a}{c}.$$

The dependence in (4.4) is used further to determine the time passing on the Earth during acceleration. The effect of the distances to the Earth and the gravity potential on the course of time is not considered for the sake of simplification [see (4.4)].

In the case when $a$ = 1 m/sec$^2$, /202

$$t_a = \frac{2.998 \cdot 10^8}{1} \arcsin \frac{1 \cdot 28.18 \cdot 10^7}{2.998 \cdot 10^8} =$$
$$= 3.66 \cdot 10^8 \text{ sec} \quad 11.63 \text{ years}$$

In the seven years of space flight at constant velocity of 28.18$\cdot$10$^7$ m/sec, the following period of time would have passed on the Earth according to (4.2):

$$t = \frac{7}{\sqrt{1 - \left(\frac{28.18 \cdot 10^7}{2.998 \cdot 10^8}\right)^2}} = 20.6 \text{ years}.$$

Thus, during the entire flight time of the spacecraft to the maximal distance, i.e., during the crew's 25 flight years, 11.63$\cdot$2 -20.6 = 43.8 years would pass on the Earth, i.e., almost double the time on the rocket.

Actually, this increase would be less. The deceleration and acceleration stages far from the Solar System are not equal in their effect on the passage of time to the analogous stages around the Earth, as is shown in Figure 46 and Table 7. Therefore, the calculations we have carried out can be considered as approximations.

Adding up the distances spanned by the rocket according to the Earth time during acceleration, steady flight and deceleration, we can find the distance (measured from the Earth) which the spacecraft has crossed. It reaches 33.3 light years (around 10 parsecs), and up to 500 stellar systems are within the range of the spacecraft.

The results of calculations of the time passing on the Earth are given in Table 8 for other values of the acceleration, corresponding to permissible distances, in 25 years of the life of the crew. As can be seen from the Table, as the acceleration increases, the craft can traverse greater and greater distances from the Earth, and the number of planetary systems within the range of the spacecraft increases more and more, while the probability of reaching an inhabited planet also increases.

The practically impossible case, in which it is assumed that a velocity equal to 94% the speed of light is attained instantaneously, is plotted in the Table. We shall call this the case of greatest distance. For the pattern under investigation, it corresponds to 73.5 Earth years (around 22 parsecs from the Sun).

TABLE 8. DETERMINATION OF THE TIME PASSING ON THE EARTH DURING 25 FLIGHT YEARS OF A GALACTIC CRAFT, AS A FUNCTION OF THE ALLOWABLE ACCELERATION AT $v_k$ = 94% $c$. /203

| Acceleration imposed, $a$, m/sec$^2$ | Acceleration time, years | | Time for a steady flight, years | | Time of round-trip flight for the ground observer, years | Max. flight range, light years |
|---|---|---|---|---|---|---|
| | For the Astronauts | For the Ground Observers | For the Astronauts | For the Ground Observers | | |
| 0.715 | 12.5 | 15.25 | 0 | 0 | 61 | 17.8 |
| 1 | 9 | 11.63 | 7 | 20.6 | 87.6 | 33.3 |
| 4 | 2.23 | 2.9 | 19.2 | 56.2 | 124 | 56.5 |
| 6 | 1.49 | 1.94 | 22 | 64.8 | 137.1 | 63.7 |
| 9.81 | 0.31 | 1.18 | 23.2 | 68.2 | 141.2 | 65.4 |
| Hypothetical case of infinitely great acceleration....... | 0 | 0 | 25 | 73.5 | 147 | 69.6 |

The Table also includes the case of minimal acceleration, where the apparatus can reach $v_k$ = 94% $c$ in 12.5 years of acceleration (half of the course in one direction). This acceleration is 0.715 m/sec . For even lower accelerations, we cannot use all the potentials of the apparatus within the range of the cited limitations; therefore, they are not advisable for a flight to the maximal distance.

It is important to mention that, in approaching very high accelerations, the gain in maximal distance decreases. Since it is extremely complicated to construct high-thrust engines, we must limit ourselves to the minimum sufficient acceleration.

Finally, let us estimate the fuel consumption for a spacecraft which completes a flight to the maximal distance in 50 years intrinsic time.

Since in any of the cases under investigation the acceleration is brought to the same maximum velocity of 94% $c$, the same amount of energy must be consumed, as calculations show, and the apparatus must be constructed for the same mass ratio (for one acceleration or deceleration): /204

$$\frac{M_K}{M_0} = 0.176, \text{ or } \frac{M_0}{M_K} = 5.7,$$

which is easily determined in each acceleration or deceleration stage by using (3.5). This means that the mass ratio of a four-stage spacecraft, corresponding to four characteristic flight periods, from takeoff to return is $(0.176)^4 = 0.00095 \quad 10^{-3}$. Thus, no more than one thousandth of the mass of the craft can return into the Solar System, i.e., only one ton for every thousand tons of the apparatus during takeoff. The remainder should be emitted in the form of the working fluid, or quanta. This means that, for a reentry weight of even two hundred tons, at takeoff the apparatus should weigh no less than two hundred thousand tons.

Let the requisite amount of energy for a round-trip flight be equal to $E = 68.1 \cdot 10^7$ Kcal for each kilogram of takeoff weight. Then, for an energy capacity of the rest mass of $E_m = 2.15 \cdot 10^3$ Kcal/kg and an efficiency of the rest mass of $\eta = 0.5$, for each one thousand tons of takeoff mass, 645 tons must be consumed to obtain the power. The structural elements of a four-stage spacecraft intended for maximal-range flight can weigh a total of one ton. The remaining 344 tons are ballast mass, which can be converted into radiation or used as reserve power.

Most of the stages of the spacecraft are ejected along the way. Moreover, the middle stages can be used. For example, the first of them, having carried out its task, can be returned to the Solar System. However, to decelerate it and accelerate it back to the Earth, the annihilation fuel reserve must be substantially increased. Its probably can be left as a unique automatic space tank in space.

The second stage is left in orbit around the flight target. The third can be used for reprocessing in the annihilation emission source.

## DISCARDING THE LIMITATIONS /205

Until now, we have assumed that only the lowest accelerations and velocities at which voyages to the stars are possible during the period of a human life could be imparted to the interstellar apparatus, and we use a mass ratio which seems technologically feasible. Discarding these limitations, going far beyond the range of the technologically foreseeable future, we can show that the quantum rocket will open up theoretically unlimited prospects for man's penetration into space.

Assuming that a rocket leaves the Earth at a constant intrinsic acceleration of $a$ = 10 m/sec$^2$, $a$ = 30 m/sec$^2$ and in the hypothetical case $a$ = 300 m/sec$^2$, and passes the half-way point to the target at a constant acceleration, while it covers the second half at a constant deceleration, the German physicist E. Sanger calculated the one-way flight of a galactic voyage for the rocket crew for different cosmic distances measured from the Earth, $L_E$.

The equation which Sanger used has the form

$$t_\text{к} = \frac{2c}{a} \arcsin\left(1 + \frac{aL_E}{2c^2}\right). \tag{4.6}$$

For a flight to substantial distances which are commensurate with the dimensions of galaxies and distances between them, this equation is simplified thus:

$$t_\text{к} = \frac{2c}{a} \ln \frac{aL_E}{c^2}. \tag{4.7}$$

For example, during a one-way flight to the center of our galaxy at a constant acceleration (and subsequent deceleration) of $a$ = 10 m/sec$^2$, we obtain in first approximation about $7.25 \cdot 10^7$ sec, or roughly 22 years.

The computations made more specific by (4.6) yield 19.7 years. The results of calculations for other accelerations are given in Figure 48, which was constructed in a convenient form (the values are plotted along the axes in logarithmic scale). It can be seen that, to span the distance to Proxima Centauri, astronauts need only 3.6 years. This may seem improbable, since a ray of light traverses this distance in only 4.27 years.

Actually, the relative velocity of the rocket $v_k$ cannot exceed the speed of light. However, as we already know, the distances for the spacecraft itself are shortened, if we judge them according to measurements of the course made by the rockets crew. Therefore, to the ground observer, for whom these distances remain unchanged, it would seem that the rocket is moving at a velocity which exceeds the speed of light. /206

Let us remember that the proper velocity of a spacecraft is the ratio between the course it has crossed according to measurements by the ordinary astronomical methods from the Earth $L_E$, i.e., calculated by the ground observer, and the time interval passing on the rockets, $t_{roc} = t$, i.e., $v_e = L_E/t_{roc}$. The distances and times are measured in different reading systems. This temporal

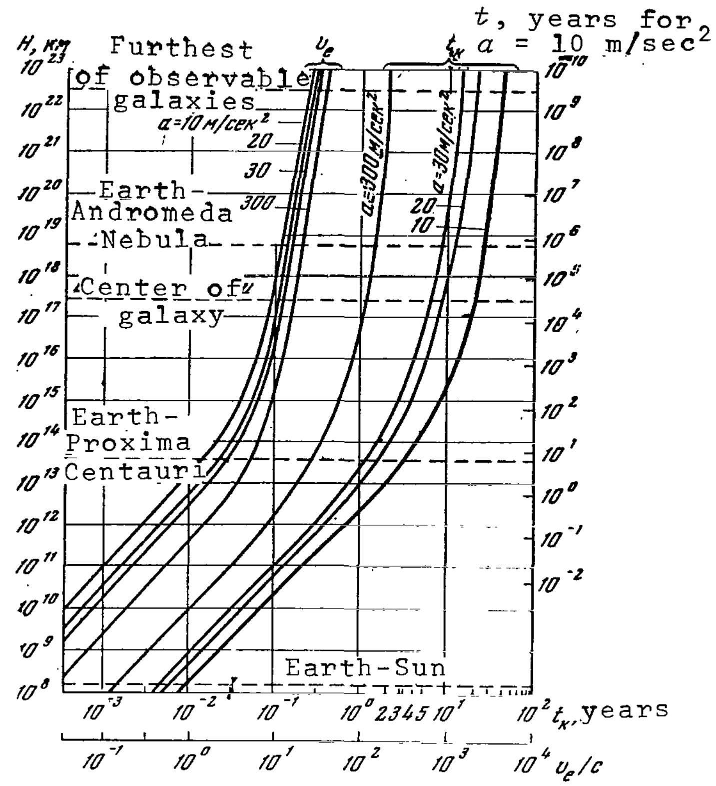


Fig. 48. Dependence of Distances Crossed By a Rocket, Permissible Flight Speeds and Time Passing On the Earth (The Latter For an Acceleration of $a$ = 10 m/sec$^2$), of the Proper Flight Time for the Rocket Crew and Einstein's Number for Different Accelerations (Uniform Acceleration for the First Half of the Course, and Uniform Deceleration for the Second Half).

velocity has no physical significance. However, it shows what distance, measured from the Earth, for the life span of the crew that the rocket travels, or the time needed for the rocket to travel the distance measured from the Earth. /207

The distances $H$ which a spacecraft will be able to span are plotted in Figure 48 along the vertical axis, as is the time passing on the Earth $t_a$ (for the case of $a$ = 10 m/sec$^2$), as a function of the time passing on the rockets $t_K$ and $v_e/c$, which are plotted on the horizontal axis.

As can be seen from this figure, during the entire flight to Proxima Centauri, ever decreasing time intervals pass for the crew of the craft, in comparison to the time passing on Earth. On the other hand, from the point of view of the ground observer, the intrinsic velocity of the craft increasingly exceeds the speed of light.

As a result, for example, a voyage to the center of the galaxy would take 19.7 natural years, or $3 \cdot 10^4$ Earth years, as shown above, and a voyage to the Andromeda Nebula and back to the Solar System, for an acceleration almost equal to that of the Earth, could be carried out by the crew in 54 years or in 3,000,000 Earth years, while, for somewhat higher but still allowable accelerations, man can reach the most remote of the observable galaxies during his lifetime. For example, in an acceleration of 10 m/sec$^2$ for a voyage to the most remote galaxies which can be seen in the most powerful modern telescopes, as well as the return trip, we would need 84 years of life of the crew. Around 6 billion years would pass in the Solar System in this time. The natural question is, should they return to the Sun? Perhaps in this time a substantial number of intelligent inhabitants of the system would have gone to another heavenly body which is richer in energy. And a second, no less important question: under what conditions should the spacecraft be sent, since it is practically incapable of returning?

Let us first examine the technological aspects. /208

Since the "fuel" consumption is determined by the time interval passing in the system of the rocket, the rest mass which should be taken on board in order to answer its power demands remains admissable in comparison with the intrinsic mass of the rocket.

However, the mass ratio of the craft which is necessary to reach a relative velocity approaching the speed of light swiftly increases, and thus the difficulties in constructing the craft also increase. Thus, the ratio between the initial and the final mass, or Tsiolkovskiy's number, would be 6.25 trillion ($6.26 \cdot 10^{12}$) for a round-trip voyage to the Andromeda. Out of 6.25 million tons of initial mass, only one gram would return to the Earth at the end of the flight!

One of the methods of overcoming some of these difficulties is the construction of intermediate power bases on the way to other stellar worlds. The craft can be equipped with mass and power directly in flight, in a manner similar to the in-flight refueling of aircraft. In this case, an electromagnetic beam similar to a laser beam transferred from the power base to the craft could possibly be used as the "flying boom".

From the Solar System to the stars, there could be chains of power stations which successively supply energy to the craft flying by, so that they may be sent further from the final link in this chain, or the last station, with the greatest fuel reserves.

The second complication in the solution to the problem, the facts that the Earth is growing unimaginably "older" during the flight time, will be eliminated to an extent when man leaves his earthly cradle for outer space, where a return will be simply unnecessary.

Despite all of the difficulties, with some of which the readers have become acquainted in this book, we are sure that galactic apparatus will be constructed in a historically conceivable future.

"What today is impossible tomorrow will be possible", wrote K.E. Tsiolkovskiy. Quantum rockets may become the magic key which will unlock the door to craft sending humans to innumerable intelligent worlds in the boundless universe.

## 5.

## CONCLUSION

The time will come when space liners will be sent across interstellar routes, but the achievements of Soviet science and technology will never be forgotten, since they first made it possible for man to set foot in the universe, and since the labor of every Soviet citizen is involved. /209

Naturally, all of our predictions were based only on those studies which are known or for which science has already paved the way. Looking into the future, we merely attempted to follow one of the paths of our age. However, it is obvious that new developmental trends will be found, new ways of obtaining energy, new methods for overcoming space and mastering time. It may be possible to supply a spacecraft with the energy of the electromagnetic fields of outer space (particularly the local ones), or the magnetic fields of an even larger scale which acts in the megaworld. It is impossible to predict future discoveries and their effects on the development of spacecraft today. That is why they are called discoveries.

Only a few years ago, in 1961, the first spacecraft went onto orbit with the first astronaut on board, Yuriy Alekseyevich Gagarin. In the short time following, together with the development of space research, our ideas on what can be achieved in outer space have expanded immeasurably.

In particular, until very recently only research studies were carried out in the field of electric rocket engines. Today, the first such engines have already been operated in space - on the /210 Soviet apparatus "Zond-2" and "Zond-3". They mark a new stage in the development of engines for a spacecraft. In only a few years, electric rocket engines will become the object of study for large groups of scientists. The same can also be said for the power sources supplying the spacecraft.

The same rapid tempo in the investigation of promising questions is also apparent in the problem of exchanging information with the civilizations of other worlds. Three years ago, this problem was treated with numerous reservations. Today, we know of a large number of studies in which this problem is investigated with the greatest possible completeness.

In closing the book, we would like to emphasize once again that one of the reasons for the regular penetration of man into space is the tendency to expand our knowledge of the worlds surrounding us and, in particular, to meet with past and present space civilizations.

Obviously, we still must wait several decades to establish the welfare of the Earth in the system of its Sun. But perhaps even at the beginning of the next century the construction of stellar craft will become the product of human labor.

Having conquered the Solar System, the communist society will take a further bold step, i.e., to the stars of our galaxy, and then other galaxies; to visit and study the planetary systems and civilizations of other worlds in order to bring other islands of intelligence into the system of the grand circle that is characteristic of the space age in the evolution of intelligent life.

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